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The October 2021 issue of *Practical Electronics* will be published on Thursday, 2 September 2021 – see page 72.

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This beauty is the ultimate in high-fidelity audio recording and playback. Use it for digitising LPs or recording your own music!

Shirt-Pocket Crystal-locked Audio DDS Oscillator by Andrew Woodfield 22
This compact little audio oscillator can fit into your shirt pocket, yet it delivers a super-accurate sinewave when and where you need it.

High-power Ultrasonic Cleaner – Part 1 by John Clarke 28
This large, High-power Ultrasonic Cleaner is ideal for cleaning bulky items such as mechanical parts and delicate fabrics. Quite easy to build, it's packed with features.

Night Keeper Lighthouse by Andrew Woodfield 36
This nightlight briefly lights up the darkness, to keep children's dreams from running aground on dangerous shores – an excellent project for beginners.

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WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

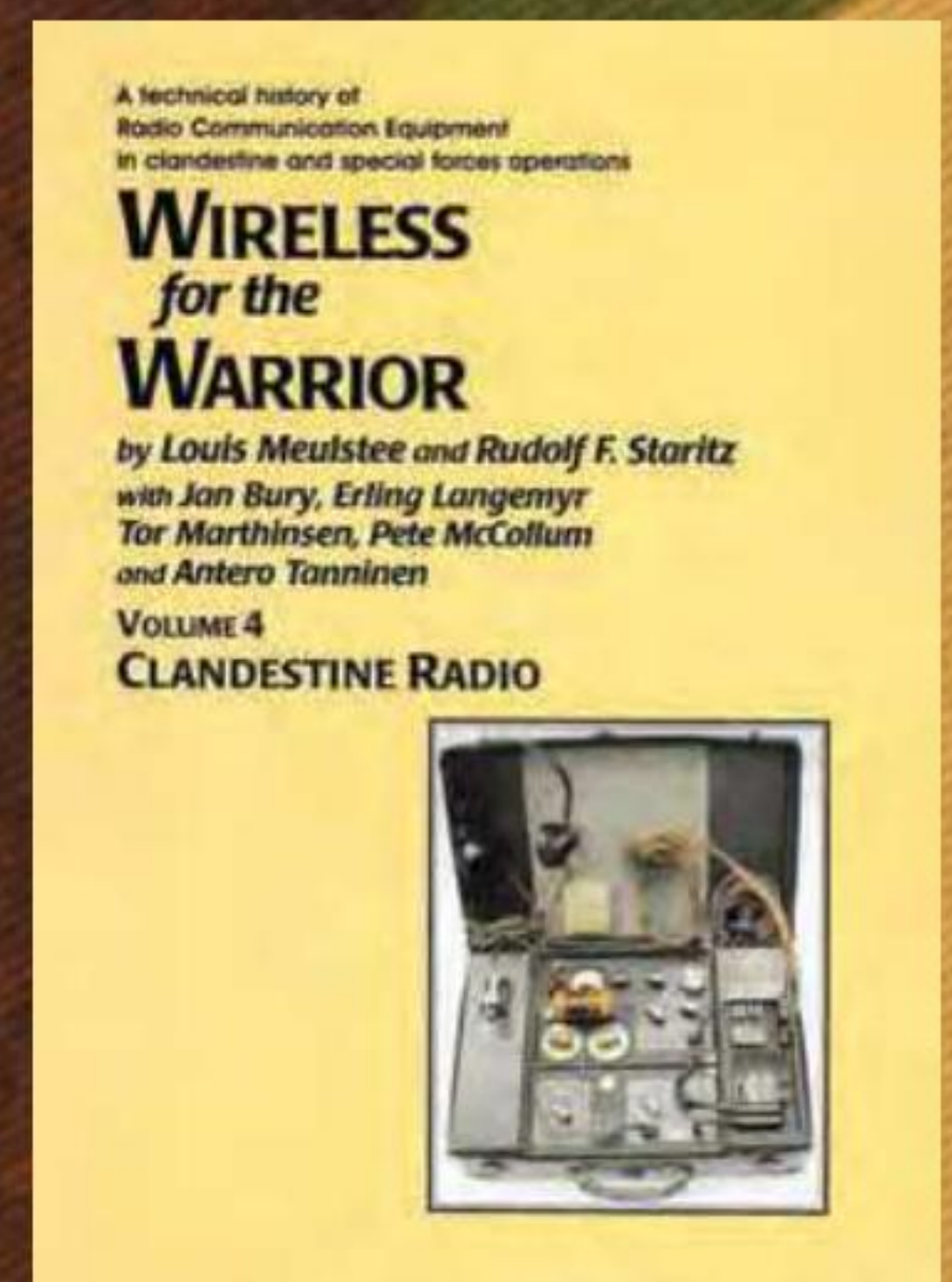
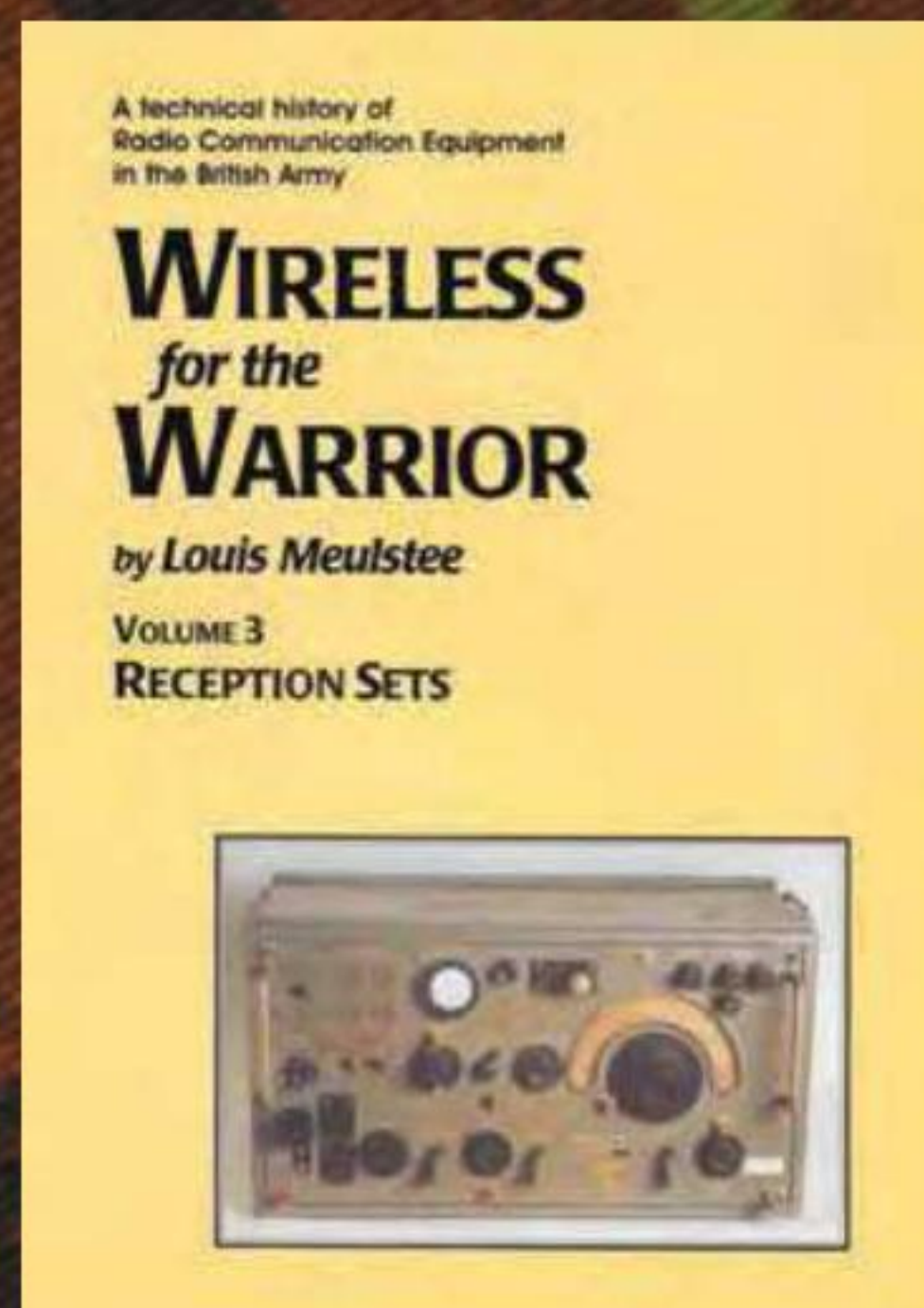
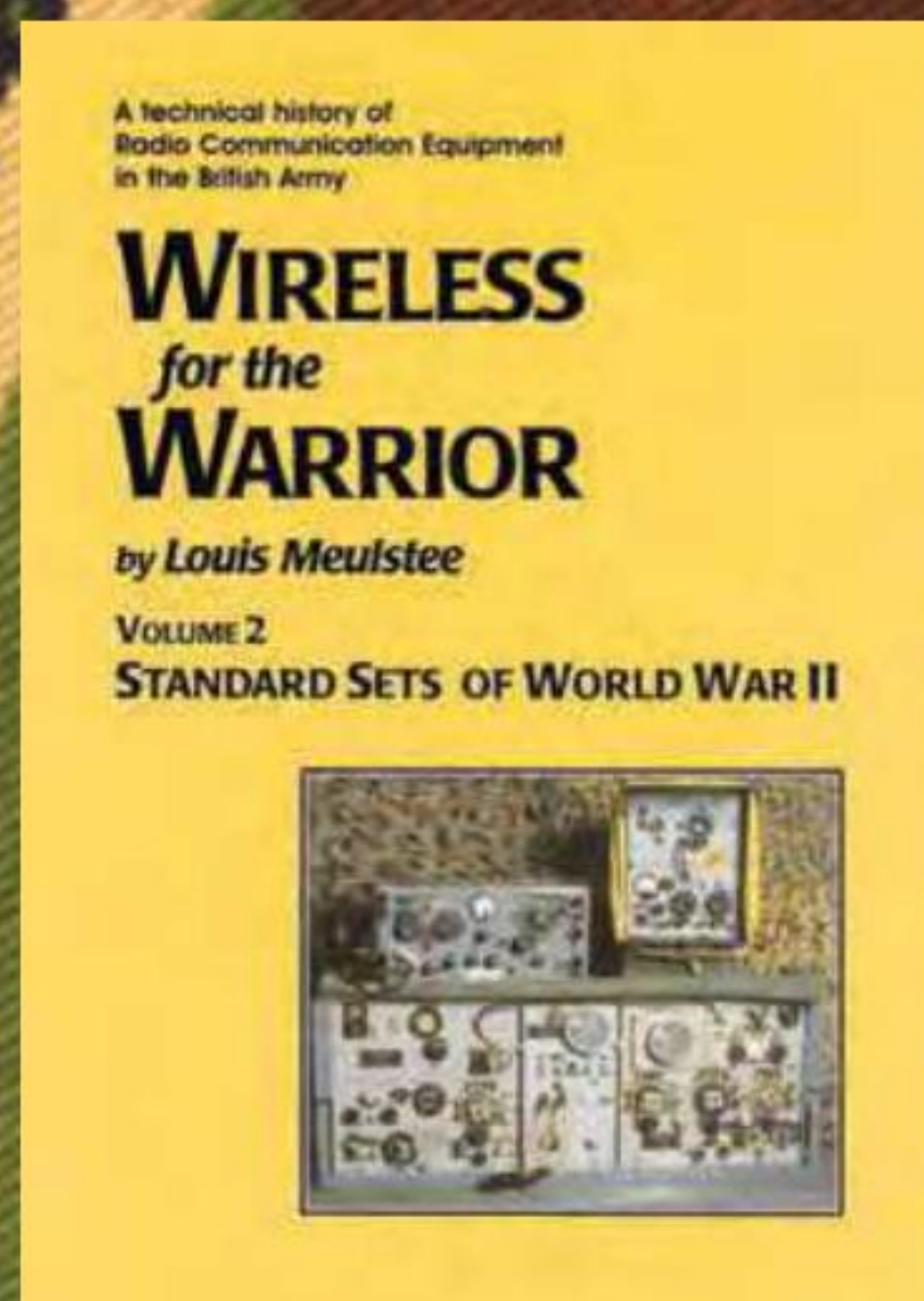
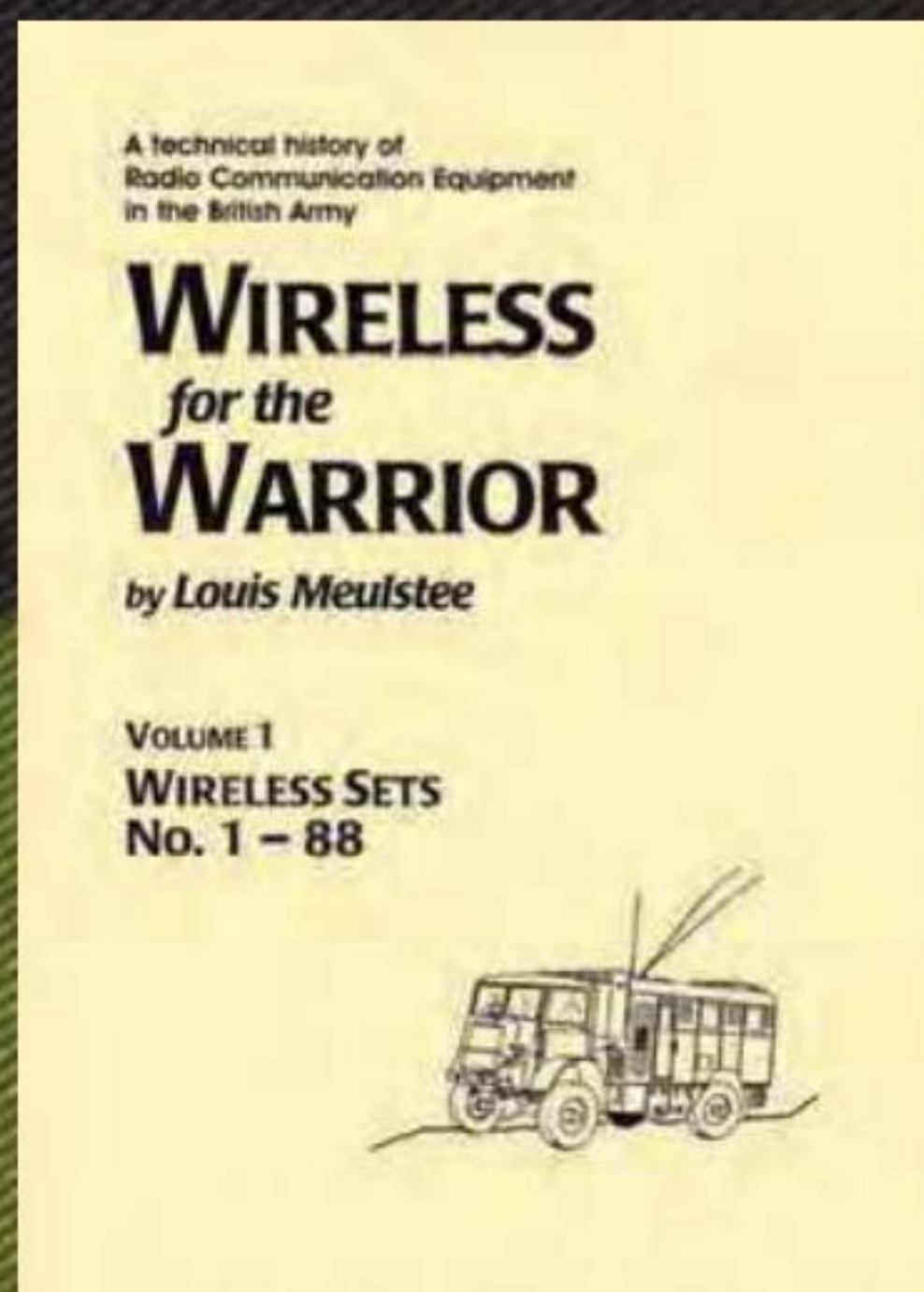
The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this

timeframe saw the introduction of VHF FM and hermetically sealed equipment.

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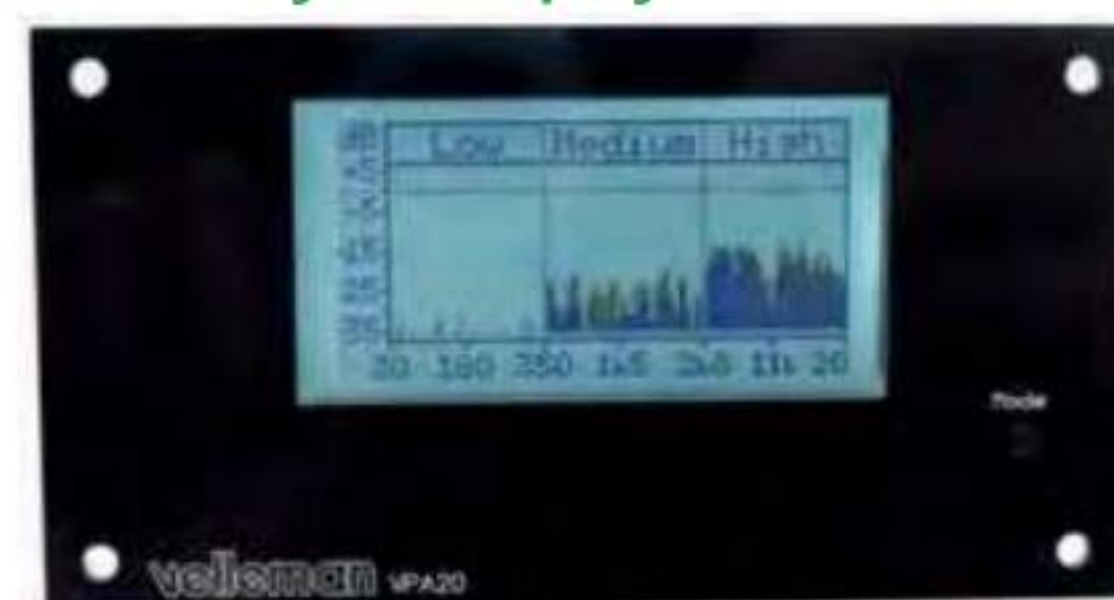


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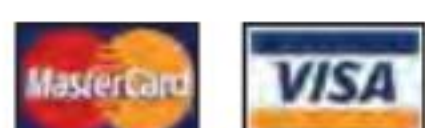
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Something for everyone and every level

One of the great things about *PE* is that we try hard to cater for every level of experience and ability. Some of our projects use sophisticated techniques and the latest silicon; others aim to get new converts to the hobby up and running. Take this issue – the *SuperCodec* project offers very high fidelity and can turn your PC into an advanced audio analyser, capable of measuring harmonic distortion down to 0.0001% and signal-to-noise ratios up to 110dB (or more with attenuators). It's a superb project, but it's not for beginners. On the other hand, this month's *Night Keeper Lighthouse* project is ideal for younger readers just starting out with a soldering iron.

Audio Out

What else do we have this month? Well, remember the old Hi-Fi maxim that 10% of your budget should be reserved for interconnects? Now, this may be an urban myth propagated by those who make their living making and selling magic-crystal-aligned phono and speaker cables, but there is certainly engineering truth in the idea that however good your design if you ignore the wires that connect up sub-systems then the overall result may be greatly degraded. Following on from his superb *Microphone Preamplifier*, Jake Rothman is now covering the design of balanced cables for microphones (and of course other sensitive applications). A must-read for all you audio and live music designers and constructors.

PIC n' Mix

Mike Hibbett's very popular *PIC18F Development Board* continues as he expands on the voltage monitoring capability developed previously by logging data to a file on a standard Micro-SD card for download to a PC. This data handling opens a whole host of useful project ideas.

Flowcode – graphical programming

This month sees the start of a collaboration between *PE* and the company behind Flowcode, an intuitive and easy-to-use system for programming microcontrollers (eg, PICs, Arduino and Raspberry Pi). The great thing about Flowcode is you can try it for free to see if you like it – no expense required. If it works for you and you need the extra modules specified for a particular project then the cost is modest and all *PE* readers get a 20% discount. Try it – you have nothing to lose!

We've all been there!

Barry Fox's eponymous column tells a tale of woe we have all experienced – how can companies that produce such clever products produce such awful guides to using their carefully crafted gadgets? Read it and weep... but Barry is nothing if not persistent, and his one-man campaign to rid the world of nonsense may bear fruit with Wi-Fi accessory manufacturer Devolo who have promised to take on board his suggestions.

Micromite?

Fear not Micromite fans! Phil Boyce is taking a well-earned break this month as he prepares a large, exciting project for the next issue – definitely worth the wait!

Keep well everyone

Matt Pulzer
Publisher

The Fox Report

Barry Fox's technology column



The curse of duff manuals

Why do big-name companies spend heavily on engineering clever new products and then provide such poor instructions that their customers cannot get them to work? I have been asking this simple question for decades, but they never learn.

German electronics specialist Devolo makes a wide range of devices for extending home networks (wired and Wi-Fi) round homes or offices, using various combinations of powerline data-through-mains and wireless connection. When you get them to work, they do work well – but ‘when’ is the operative word.

A right mesh

I tried the latest Devolo kit (Mesh Wi-Fi 2), in the hope that it would be easier to get up and running than the previous kit I tried (Magic 2 Wi-Fi). As the name suggests, the new Devolo system relies on Mesh technology (intelligent co-operation of separate Wi-Fi units) in addition to a new standard for carrying data over mains at higher speed (G.hn).

Although it's not clearly explained, one practical advantage of meshing is that all the adapters transmit the same Wi-Fi SSID and use the same password, which is the same as the router name and password. The router's own Wi-Fi can then be turned off if you wish.

The Devolo adapters all have red and white LEDs and push buttons, and the user needs to know which button on which device to press, in what order, when and for how long, what the many combinations of steady and flashing colour states signify and how long to wait for states to change before assuming something has gone wrong. Without a clear installation guide, it's a trial-and-error nightmare.

The multi-lingual printed guide that comes with the Devolo Mesh kit starts by advising users to download an Android or Apple phone App, and the App then tells the user to scan a QR code on the packaging to correctly identify the product.



Devolo's Mesh Wi-Fi is a good product – but *only* if you can actually get it to work.

Sounds good, but the QR code did not work for me with the Android App, so my only option was to use the printed multi-lingual *Installation Guide*, which Devolo provides for those who ‘prefer to carry out the installation without the App’. I did not ‘prefer’. I had no choice.

The printed manual is sketchy, disjointed and confusing, with some apparently incorrect references to the LED flash, steady and colour states. It also, Devolo acknowledges, fails to mention the vital need to complete various plug-and-press tasks within a 3-minute window (or 2-minute, Devolo seems unsure of which) and when and how to use the hidden reset pinholes, which are not even mentioned.

After many unhappy hours spent struggling with the manual I kept thinking of what Morecambe and Wise said to Andre Previn – we're playing all the right notes but not necessarily in the right order (<https://bit.ly/pe-sep21-mandw>).



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No go

To cut a long and painfully time-wasting story short, and after many start-overs after resets, some of the adapters stubbornly refused to pair and mesh, showing unhappy red lights when they should have been glowing happy steady white. I downloaded and installed the latest version of the Windows control software called Cockpit and followed its advice on pairing 'instead of pressing the physical button on the device itself'. But still no joy.

The human touch

Eventually, I contacted Devolo Care Support who very helpfully guided me through several fix tricks which finally got all three adapters working – each showing two steady white lights. But I had to admit to myself I was not sure which fix had done the trick. And I don't like relying on trial and error, so I bit the bullet, and started again from scratch, making notes of what worked. It is interesting to compare these with the steps given in the manual.

The Morecambe and Wise instructions tell the user to:

1. Plug two adapters into a power socket and wait until the Home LED flashes white quickly. Plug in the third adapter and connect to the router by Ethernet cable. Encryption takes place automatically and the Home LEDs flash white. But mine continued to glow steady white and unhappy red.
2. Press the Home button – on which adapter, pray tell?
3. Within 2 minutes press the WPS button on the router. Once the LEDs are all flashing white continuously the process is complete. But not for me; the white/red state persisted.
4. If pairing is 'unsuccessful', press Home button on all three adapters and once 'all LEDs light up white, the pairing has been completed successfully'. Sadly not. Two units happily showed both lights steady white but the third still had one stubbornly flashing red light.

Using the advice given by Devolo Care as a springboard, this is what worked for me:

1. Plug all adapters into a mains strip, press the hidden reset button on each with a paperclip for 10 seconds or more until both lights go out, and then stop pressing.
2. With the three adapters still plugged into the power strip, and one of them connected by Ethernet cable to the router, (choose any, because all three adapters are identical) wait several/many minutes for both lights on all three adapters to glow steady white. This set the adapters in a state where each had its own pre-set Wi-Fi password, so not meshed.
3. I gave up on the advice to press WPS buttons on the adapters; instead, I used the Cockpit computer software; find and follow the Wi-Fi Mesh option, then Wi-Fi Clone and Configuration with a WPS button press on the router.
4. Unplug the adapters from the power strip, leisurely locate them round the house and wait a few minutes for the LEDs to all show steady white.
5. Then, if you wish, access the router with a Browser address (192.168.1.254 for mine) and switch off the router Wi-Fi to check that its SSID is being used by the adapters.
6. At all times remember to start the button pressing steps within 2 minutes, or some adapters will be in pairing mode and others not – and resetting or re-plugging will not help because a reset adapter will be in pairing mode but the others not.

Devolo acknowledges the basic error that the manual fails to warn that all three adapters must be plugged in within 2 or 3 minutes (take your pick) but recommends my get-things-working steps 'only if the installation according to the enclosed booklet did not work' and if the adapters need to be reset, 'because when first plugged-in new adapters are automatically in pairing mode, just like after the reset.'

Also, says Devolo, 'as a rule, the adapters find each other when they are plugged directly into different rooms' but be sure to 'plug in all adapters within 2 minutes'.

So, you had better be fast up and down your stairs.

Devolo comment

Devolo also says that 'the adapter that is plugged in first passes its Wi-Fi data to the other two...(so) the adapters match each other with the same SSID and the same Wi-Fi key... we call this function 'config sync', which can also be deactivated in the menu of the configuration page under 'system'. So where in the manual is that explained?

Devolo says, 'we have made the instructions and the pairing of the adapters as simple as possible... only a few customers contact support who have problems with the initial installation.... however, you can be sure that we will continue to work on making instructions even more optimal (and) have therefore passed on your tips to the Usability Task Force (who) have already declared that they will take your feedback on board.'

Dare I hope that this will involve someone at senior management level in Devolo simply watching a guinea pig new owner struggle with the existing manual, and then revising/scrapping and re-writing accordingly?

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Do you have a telephone line supplied by BT, Virgin Media or one of the other network providers? If so, its underlying technology is about to change fundamentally, and the changeover might hit you in the pocket.

It was half a century ago when we in Britain began a comparable technology turnaround. With wide publicity, work began in 1967 to convert around 20 million appliances from so-called town gas to natural gas piped in from under the North Sea. From start to finish, the conversion process took around ten years to complete, and modification of consumers' appliances was carried out entirely at the gas supplier's expense.

The task facing Britain's telephone companies today is not identical. However, the magnitude is similar (there are around 33 million fixed-line telephone subscriptions in the UK according to www.statista.com) but the timescale is far shorter (about five years). Our existing analogue telephone network will be replaced by voice over internet protocol (VoIP) technology, in which speech is transmitted as packets of digital data in the same way as your broadband service. Customers who do not have broadband at the time of conversion will be provided with a modem hub free of charge, since conventional telephone exchanges will no longer be used. Fortunately, your telephone number will not change, and telephone users should not notice any degradation or difference other than clearer calls.

It's happening already

BT and Virgin have already started their conversion processes, which in some (but not all) cases includes replacing your existing copper telephone connection with an optical fibre. The rollout is a piecemeal process and customers will be informed when their line is due to be converted. You cannot jump the queue, as the only way that conversion can be carried out economically is on an area-by-area and street-by-street basis. Just to recap, the entire changeover is planned to be completed by the end of 2025.

The existing analogue network is being abandoned by all the UK's telecomms providers and you cannot have your old copper lines reinstated. Conversion is not a matter of choice either. If you are

wondering what the brave new world of post-conversion will look like, take a peep at <https://bit.ly/pe-sep21-vm> and <https://bit.ly/pe-sep21-bt> (yes, I know that other telephone providers exist, but we don't have space here to give links to all their websites).

Probably the most striking difference from the great gas conversion of the Swinging Sixties is that whereas that operation did not leave consumers out of pocket, the same cannot be said for all of today's phone users. Taking just one example, BT's helpful footnote for its new Digital Voice offering states, 'If you have special services, like a monitored burglar alarm or health pendant, you'll need to let your provider know you're moving over to Digital Voice.' That is something of an understatement! When I had my security alarm serviced last week, I asked the technician whether it would still work with Digital Voice. He told me that my alarm was totally incompatible and I would have to have a brand-new system installed for £299 plus a substantially higher monthly maintenance charge. I foresee some frank and lively discussions ahead!

Legacy equipment

Will your existing cordless phone and answering machine work on the new system? Who knows?! Despite conflicting statements online, it appears that in most cases your phones and gadgets will operate if plugged directly into the new hub that your telephone company will provide. This means diverting your extension wiring into the hub, assuming you have the DIY skills.

BT has a workaround for this. Its cunning plan is to give the latest version of its Smart Hub 2 the ability to act as a cordless telephone base station and to sell mains-powered wireless adapters that make extension telephones and answering machines connect wirelessly with the hub. The product is called a Digital Voice Adapter, item code 101488. It plugs into the mains, and it registers on the BT Smart Hub 2 in the same way

as the BT Digital Voice phone that you receive when your line is converted to digital. You then plug your third-party DECT cordless base station or any other phone into it (more details at: <https://bit.ly/pe-sep21-dva>). Note that older phones fitted with rotary dials will not work on the new system unless you get hold of a pulse-to-tone converter from a third-party manufacturer (these converters do exist, and they work amazingly well).

Power problem

The new digital phone system comes with a vulnerability that you need to be aware of. One of the reassuring features of today's analogue telephone service is its independence of power cuts. Unless it's a cordless handset, your existing telephone is powered not from the mains but by substantial batteries located at the telephone exchange. If the lights go out at your place, you can still make phone calls. This is not the case with the new digital systems, which all depend on mains electricity to power the hub and any other gadgets. If the power fails, you cannot call for the police, ambulance or fire brigade. You cannot rely on a mobile phone either, because many smaller cellular base stations have no battery backup and will go off air immediately in a power cut. (All too frequently, these towers remain off air for several hours when the power fails.)

Battery backup for your hub and phone system would mitigate this vulnerability, disregarding how ugly and ungainly rechargeable batteries would be. As of now, it is unclear whether telephone companies will be forced to provide backup batteries for their digital telephone users by default, but the current expectation is these will be available only on request, at your cost, and might work for only an hour. An hour's functionality will be a fat lot of good when a tree severs an overhead power line or when there are blizzards and snowdrifts. Burglar alarms and vulnerable folks' emergency assistance alarms will be unable to connect. Not very encouraging, is it?

Win a Microchip AVR128DB48 Curiosity Nano Evaluation Kit

Practical Electronics is offering its readers the chance to win a Microchip AVR128DB48 Curiosity Nano Evaluation Kit (EV35L43A) – and even if you don't win, receive a 20%-off voucher, plus free shipping for one of these products.

Take your next idea to market with a development board that you can keep in your pocket. With full program and debug capabilities, the AVR128DB48 Curiosity Nano Evaluation Kit offers complete support for your next design.

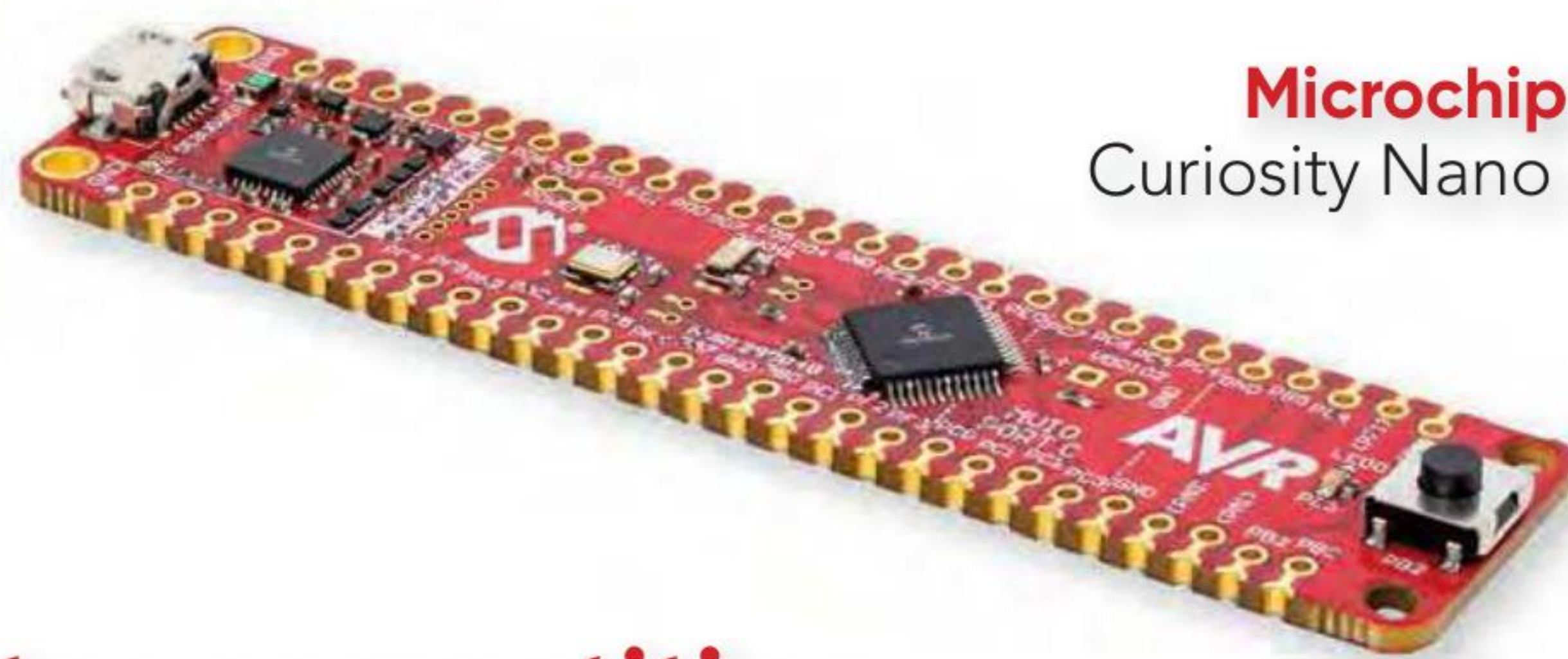
The AVR DB family of microcontrollers feature the well-known AVR CPU, now running at up to 24MHz across the full supply voltage range of 1.8V to 5.5V. The family includes 32KB, 64KB, and 128KB Flash variants in 28- to 64-pin package options. The AVR DB family is designed to bring analogue signal conditioning, real-time control and multi-voltage operation to applications including industrial control, home appliance products, automotive and Internet of Things (IoT).

The USB-powered kit features an on-board programmer/debugger that seamlessly integrates with MPLAB X and Microchip Studio Integrated Development Environments (IDEs). Its small form factor makes the board excellent for breadboard soldering or you can combine it with the Curiosity Nano Base for Click boards, which features multiple mikroBUS sockets so you can easily add sensors, actuators or communications interfaces from Mikroelektronika's extensive selection of Click boards.

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Microchip AVR128DB48 Curiosity Nano Evaluation Kit

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<https://page.microchip.com/PE-AVRDB.html>

Closing date

The closing date for this offer is 31 August 2021.

May 2021 winners

Mike Hades

He won a Microchip ATtiny3217 Xplained Pro Evaluation Kit



Net Work

Alan Winstanley

This month, *Net Work* looks at the upcoming release of Windows 11 and the requirement for TPM; Cloud backups; and the rise of Virgin as a satellite launch provider.

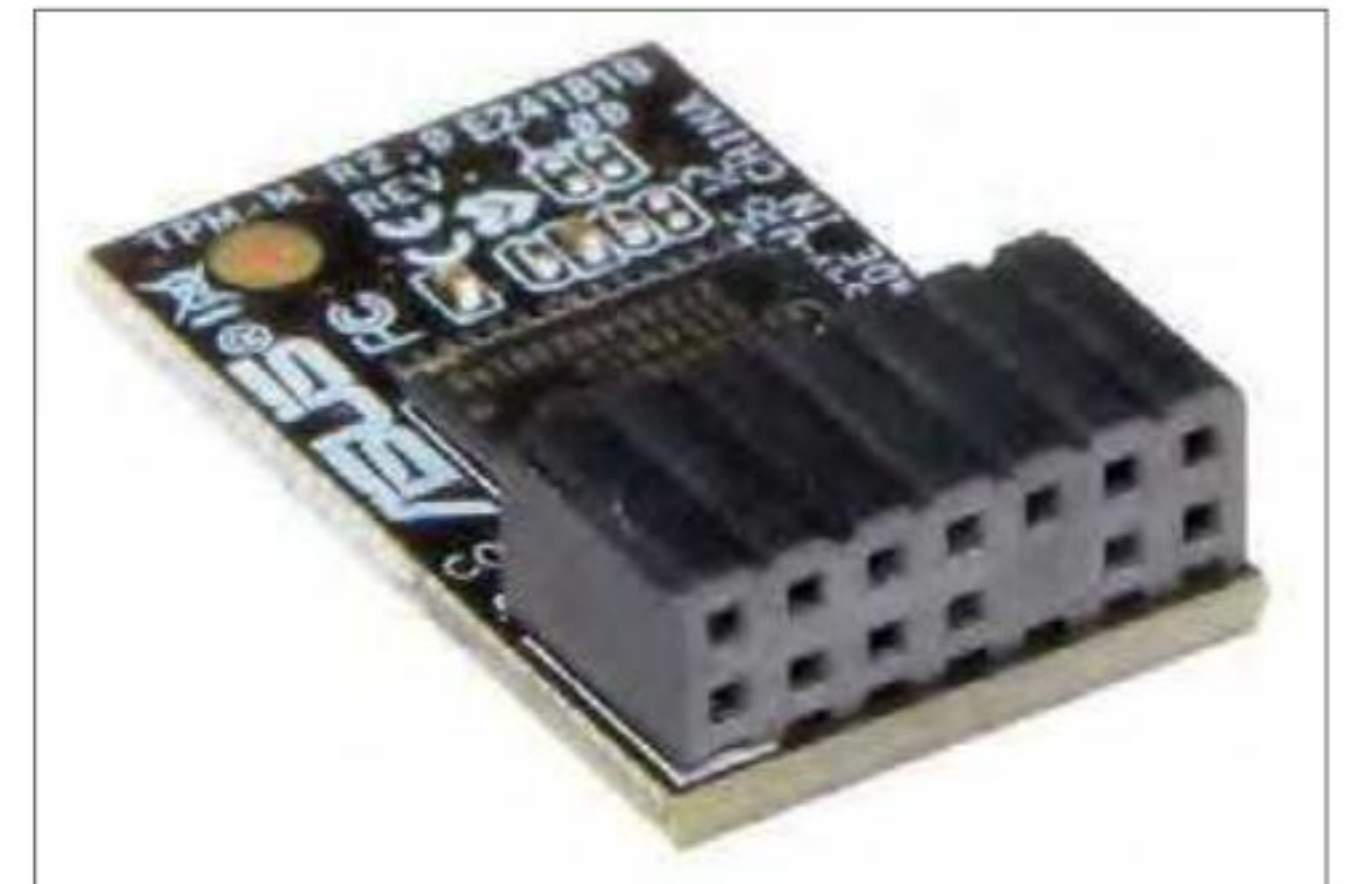
Although *Net Work* isn't a computer column as such, home computers are omnipresent in our networked lifestyles and consequently the subject regularly creeps onto the *Net Work* agenda. Our own heritage was built on the Windows and DOS-based PIC micro projects that our late technical editor John Becker famously designed from the 1990s onwards, complemented by generous amounts of free DOS or Windows software. Generally speaking, we think that most *PE* readers gravitate towards using Windows PCs or laptops for their technical work or hobby. From the electronics hobbyist's point of view, 'IBM-compatibles' have over the years proved more accessible, cheaper and easier to support than highly proprietary Macs running macOS, which is why things are somewhat Windows-centric around here, with Linux voted a popular runner-up among readers.

This brings us to the next big event on the home computer calendar: the release of Microsoft's next operating system, Windows 11, which is just around the corner and likely to start rolling out well before the year end. Judging by Microsoft's mid-year teasers on the new release, after users battled with 18 months of Covid-19

lockdowns, the new OS places more emphasis on making your desktop more manageable and productive. The aim is to better handle a new-found 'hybrid' way of working and playing. Windows 11 promises to connect people together more easily using its group collaboration package, Microsoft Teams. End users can expect cloud-based services (Microsoft 365) to be more heavily integrated in the updated OS, which will also allow users to see their most recent files regardless of the platform (Android, iOS) being used. There will be new support for Windows gamers too, Microsoft says, and better exploitation of touchscreen devices (which includes some laptop screens).

It was Windows 1.0 that gave IBM-compatible users a graphical user interface alternative to the DOS prompt (see the 1986 Steve Ballmer promo: <https://youtu.be/EtuDS0ntaJY>) and eventually Windows 95/98 and XP followed on. Mac users will be flattered to see that the Windows 'Start' button, previously tucked away at the bottom left since the days of Windows 95 (see the original W95 ad on <https://youtu.be/OPyWDMmYJhQ>) has finally been moved along to the bottom centre of the screen in Windows 11, and pop-up menus are now centralised along the

bottom edge too, according to some early screenshots. It seems that applets and dialogue boxes finally have radiused corners – gone, hopefully, will be those stark and confusing 'Metro' tiles and flat scroll bars (maybe) that often confuse or impede workflow on busy desktops. In Windows 11, desktop layouts can also be configured as workspaces optimised to handle



A typical Trusted Platform Module (TPM) intended for retrofitting onto compatible motherboards. Windows 11 requires TPM2.0 to be present.

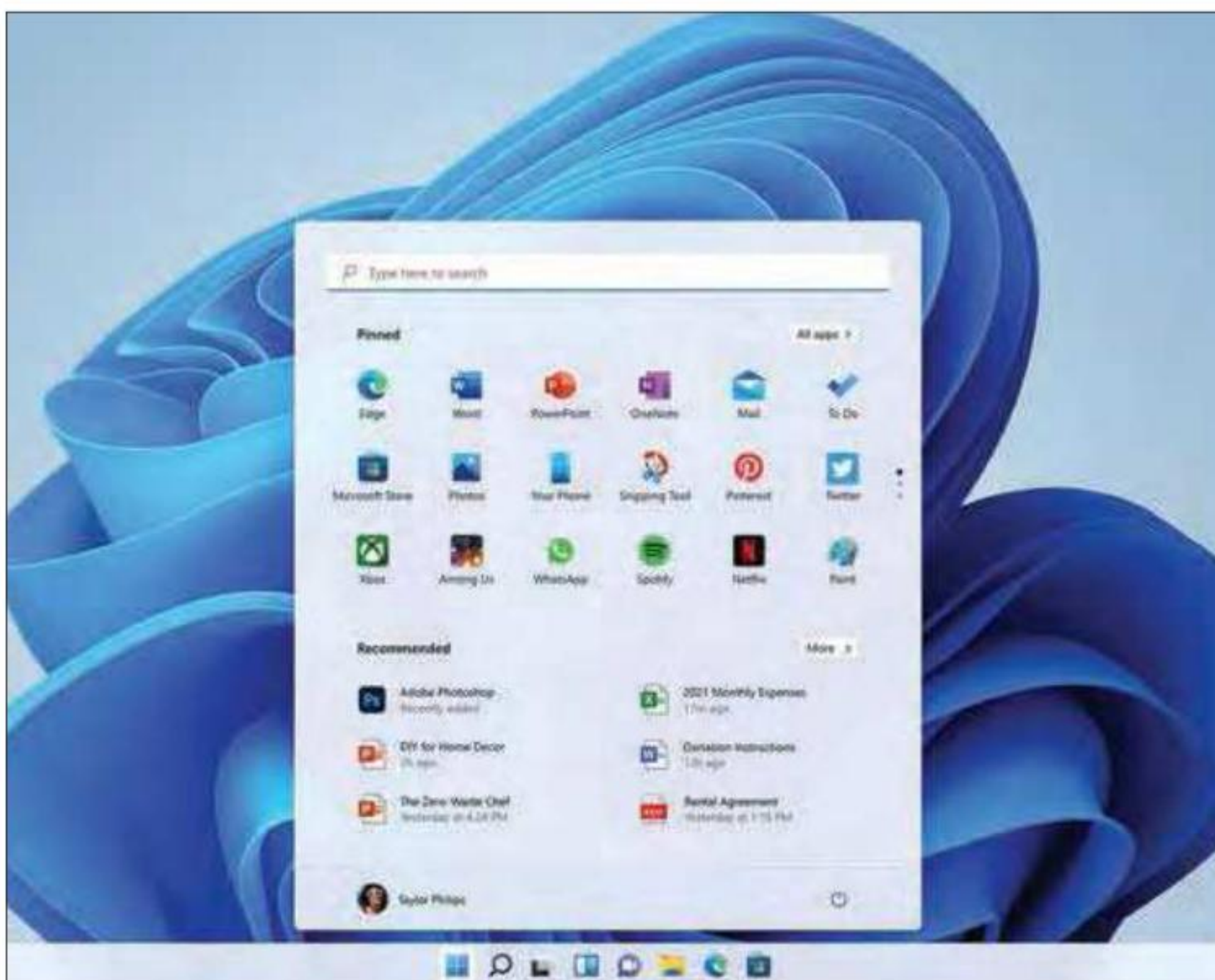
different tasks.

Details are still emerging, but Windows 11 is expected to be available as a free download to existing Windows 10 owners. Microsoft remains silent on the actual timetable, but before considering upgrading their W10 PC, readers need to be aware of one very big catch: not every PC will be compatible with Microsoft's new OS. There is a possibility that older machines may end up stuck with Windows 10 (already six years old) until they reach end of life and are no longer supported.

Windows 11 and TPM

A major aspect is that Windows 11 requires PCs to provide a Trusted Platform Module (TPM). Windows 10 can already utilise a TPM (eg, for Bitlocker disk encryption, or perhaps business applications that utilise Windows Hello) but Windows 11 will make a TPM compulsory. This cryptographic module plays a hard-wired, hardware-level authentication and privacy role that software alone cannot ever achieve. Windows 11 will require TPM 2.0 to be present on the PC's motherboard.

The good news is that many current-generation PCs probably already have a TPM on board, either embedded as part of a chipset, or alternatively a header on some motherboards may allow a TPM to be retrofitted. Needless to say, as soon as specs for Windows 11 went online in June, the newswires were electrified with talk of 'TPMs'



Early screenshots of Microsoft's forthcoming Windows 11 operating system show a centred task bar and Start button.

and the price of retro-fit TPM 2.0 modules quadrupled overnight, all for a new OS that won't be released for many months yet. So-called 'scalpers' moved in to scoop up stocks, and at the time of writing the price of these tiny modules has almost reached the cost of a whole new motherboard. A typical TPM module is made by Asus (see: <https://bit.ly/pe-sep21-tpm>) but enthusiasts are already bemoaning the fact that supplies have dried up – this on top of a global semiconductor shortage, remember.

PC hobbyists can easily check whether their motherboard has a separate TPM header, but there's no guarantee that older motherboards may be compatible with the newer standard TPM2.0 module required by W11. Most systems from recent years already have TPM capability built in, we're told, possibly under another guise. For example, the author's current home-brew PC has a 'Secure Boot' feature that can be enabled in the BIOS and (happily) its maker Asus has already confirmed that it will be compatible with Windows 11. This is despite the fact that an early release of Microsoft's TPM Checker Tool reckoned my board was not compatible when I tried it. (The TPM Checker Tool has since been withdrawn while Microsoft refines it.) So, check the maker's spec sheets, and check BIOS settings too in case you have to enable TPM manually.

Early shots of Windows 11 look appealing and it's worth keeping a lookout for news of Windows updates, as the upgrade may be delivered as a 'routine' Windows update. Windows 10 users can type 'winver' straight after hitting the Start button, which will confirm your current version (21H1 probably), or type 'update' to launch the Windows Update applet to check settings there.

Readers can expect to see lots more news, views and confusion emerging about forthcoming Windows 11 and the need for a TPM, and more information about TPMs is published by Microsoft at: <https://bit.ly/pe-sep21-ms>. A somewhat glitzy introduction to Windows 11 is available on YouTube at: <https://youtu.be/Uh9643c2P6k>

The scourge of ransomware

Last month's *Net Work* summarised some of the latest appalling ransomware attacks that have blighted major Western utilities, commerce and public services, yielding multimillion dollar ransoms for the miscreants. The scourge of ransomware continues unabated, and the news just gets

worse: on Friday, 2 July, just before the 4 July holiday weekend in the US, a highly sophisticated attack believed to originate from inside Russia and perpetrated by the REvil ransomware gang, hit the US company Kaseya's VSA (Virtual Server/Administrator) remote monitoring and management

software which is used by thousands of clients to manage IT infrastructure.

The result was that Kaseya inadvertently distributed an infected 'routine' update to about 60 managed service providers (MSPs). These are at the top of the tree, so they re-distributed infection down the line to their own customers. This latest 'supply chain' attack may have hit up to 1,500 users whose systems had to be taken entirely offline. The attack reached five continents and, in one example, a whole chain of Swedish supermarkets had to go offline because their cash register systems had been wrecked.

Ironically, Kaseya was already in the process of patching a newly reported zero-day vulnerability (one that the software vendor knows about, but has yet to patch it) when the hackers struck, exploiting exactly the same vulnerability. This led to speculation that the hackers were maybe monitoring internal communications and decided to strike before it was too late, so they chose a key US holiday weekend when IT staff resources would be thin on the ground. It was reported that more than 1,000 servers and workstations had their data encrypted as a result, and a ransom note was delivered demanding \$70m payable in BTC (Bitcoins), making this the worst case of ransomware ever perpetrated. At the time of writing, Kaseya were being very tight-lipped about whether a ransom would be paid, but FBI and cybersecurity investigations are ongoing.

Glacial backups

So-called MSPs are juicy targets for supply-chain attacks like these because just one lucky breach can snowball globally, yielding high returns for the blackmailers. For home users and small or micro businesses, damage from a virus or ransomware might be proportionately higher, so consider taking off-site backups of precious



Amazon S3 Glacier is low-cost cloud storage intended for archiving slow-moving data that doesn't require instantaneous retrieval.

data, perhaps utilising globally distributed cloud-based solutions such as Amazon S3 Glacier. This low-cost archiving service is designed with long-term backup in mind, and consequently it 'restores' more slowly – anything from a few minutes to three to twelve hours to retrieve data – but various price bands are available that allow customers to pick the speed of service. Costs also relate to the volume of data transferred 'in' or 'out' of Glacier. Large numbers of corporate and local government organisations worldwide now use Amazon AWS (Amazon Web Services), and more details and pricing of Glacier archive storage is available from: <https://aws.amazon.com/glacier/>

At home-user or small-office level, data stored locally on a network-attached storage can also be backed up silently to the cloud. For example, the author's preferred Synology NAS offers various Diskstation packages (not tested by the author) that archive data on Amazon S3, Amazon Glacier or Microsoft's Azure, but Synology also offers its own cloud-based storage called Synology C2, hosted in the US and Germany. Synology owners can learn more online at: <https://bit.ly/pe-sep21-syn> under 'Package'. Coming soon are Synology C2 Password, an interesting-looking service for storing credentials securely in the cloud (see: <https://youtu.be/gEDCCq5COXw>), and Synology C2 Backup that allows individuals to back up all their Windows devices (<https://youtu.be/u67BkolfBg4>). As mentioned last month, consider too taking a last-gasp 'air gapped' backup onto a pocket drive or SSD.

Antivirus auto-renew rebates

Last month's column gave a quick run-down of popular antivirus packages for home computer users and typical prices were given for versions that could be downloaded using an Amazon account



Virgin Orbit's 747 carrier aircraft 'Cosmic Girl' takes off from Mojave Air and Space Port in California with LauncherOne underwing for the company's *Tubular Bells: Part One* mission. (Image: Virgin Orbit)

– for example, for an introductory price. Antivirus software is typically licensed by the number of devices and the number of years they run for. Most businesses and commerce hate the idea of consumers re-considering a service every year before renewing, in case of course they decide to cancel. Instead, they try to sleepwalk customers into seamlessly coughing up a fee for another year (direct debits are good like that) without thinking about it. Indeed, we're often told we, 'Don't have to worry about a thing' as the service/tax/insurance will be automatically charged when it's due for renewal – as if we should feel grateful.

I counselled against choosing 'auto renewal' of antivirus software because subsequent years can quietly slip through at a much higher price. Because of this, the UK's anti-virus market has been under investigation by the UK Competition and Markets Authority (CMA), and Norton Lifelock was finally taken to court for refusing to provide the CMA with information surrounding their auto-renewal policies. In June, Norton agreed to extend the cancellation rights of auto-renewal consumer contracts, see: <https://bit.ly/pe-sep21-cma1>

In May, the CMA did the same with McAfee. Users of this product should check the online judgment to see if they (now) qualify for a backdated refund: <https://bit.ly/pe-sep21-cma2>

Virgin Orbit and Spaceport Cornwall

Net Work readers will know of the remarkable achievements of SpaceX, which is currently building a global

satellite network to beam broadband services down to earth. One can only marvel at the way in which 60 satellites are projected into LEO after each launch and the re-usable booster rockets are recovered again, often landing vertically on a drone ship like something straight out of science fiction. The satellites use optical links and trials are also under way to communicate by laser with airborne military drones. SpaceX also offers 'rideshare' flights that enable individual satellite owner-operators to hitch a lift alongside many others.

Despite all these advances in technology, one headache that SpaceX must contend with is local weather conditions, which sometimes causes rocket launches to be postponed until another launch window opens. It's also not viable to launch a rocket without a full payload. Meantime, aviation entrepreneur Sir Richard Branson (the name behind Virgin Records, Virgin Atlantic and Virgin Galactic – see July 2021 issue) is offering a more affordable and flexible launch service for small satellites that will avoid customers needing to queue up for a rocket launch: just book a ride on a 747 instead!

Operating jumbo jets is something that Richard Branson knows an awful lot about. By adapting a 747-400 to carry his 'LauncherOne' rocket slung underneath, his Virgin Orbit business aims to offer a fast-track, lower-cost satellite launching system and the service is already at an advanced stage of testing, Virgin Orbit says. Kendall Russell, speaking for Virgin Orbit, told me that although the LauncherOne rockets are expendable, the 747 itself does most of

the work in reaching the upper atmosphere and is of course entirely re-usable.

At the end of June, they successfully completed a rideshare mission deploying seven satellites into space using an air-launched LauncherOne, including four CubeSats for the US DoD – who are always keen to explore new options – and the Royal Netherlands Air Force's first military satellite. The Virgin Orbit mission was called *Tubular Bells: Part One* as a nod to the first vinyl album ever published by Richard Branson's Virgin Records back in 1973, which some of us will remember playing on our record decks and transistor amps of the time.

Virgin Orbit has some ambitious and potentially market-disrupting launch plans, and it may well carve itself a niche for launching small satellites quickly and without operators needing to queue up at a space port. There are more exciting plans in store, including building a launch facility at Spaceport Cornwall in England, with launches from a brand-new airstrip slated for 2022. Essentially, Virgin Orbit simply needs a 747-sized runway and some ground infrastructure in order to be up and running in the satellite launching business. You can learn more at: www.virginorbit.com <https://spaceportcornwall.com>

OneWeb update

Finally, this month, London-based satellite datacomms firm OneWeb has been busier than ever, having successfully placed 36 more satellites into low-earth orbit in July to complete its 'Five to 50' (degrees latitude) coverage using 254 satellites. The firm hopes to roll out commercial services before the year end. Part-owner Bharti Global is also aiming to invest a further \$500m into the part-UK-government owned OneWeb, subject to regulatory clearance, with Bharti becoming the largest stakeholder in the firm, hard on the heels of a \$550m investment from Eutelsat announced in April. This too is subject to approval, and some discontent has been expressed within the EU, citing Eutelsat's possible conflicts of interest with potential EU-based satellite broadband projects. OneWeb also recently signed an MOU (memorandum of understanding) with Britain's BT to explore the supply of satellite-based broadband to hard-to-reach areas of the UK, while also looking to expand its services for BT customers globally.

See you next month for more *Net Work!*

The author can be reached at:
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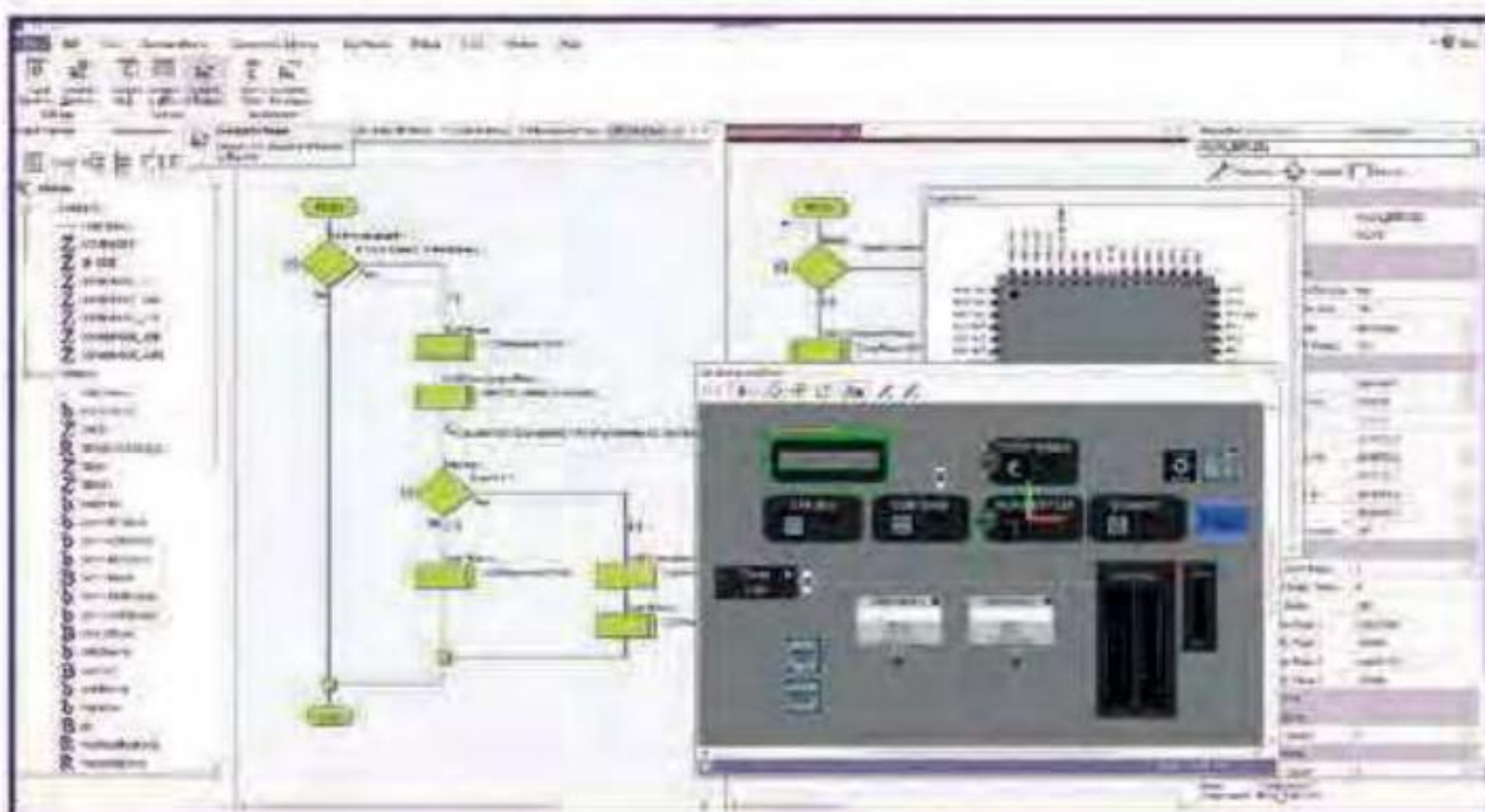
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This beauty is the ultimate in high-fidelity audio recording and playback. You could use the *SuperCodec* for digitising LPs, recording your own music or playing music with a very high-quality stereo amplifier driving excellent speakers. It can also turn your PC into an advanced audio analyser, capable of measuring harmonic distortion down to 0.0001% and signal-to-noise ratios up to 110dB (or even more, with suitable attenuators).

This project was inspired by a reader who wanted to digitise his LP collection, and asked us if we had a USB sound interface that would let him record with very high fidelity.

If you want better quality audio for your PC, including the ability to record and playback at high sampling rates and bit depths (up to 192kHz, 24-bit), then read on.

In addition to recording and playback of music or other audio, this project enables your PC to become an advanced audio quality analyser. You just need the right software; we'll get to that later.

With the addition of the *2-Channel Balanced Input Attenuator for Audio Analysers and Digital Scopes* from the May 2016 issue, you will have a potent measurement tool indeed.

It allows you to measure the distortion performance of the very best amplifiers, preamps, equalisers and other audio devices.

In designing this project we started by looking for a simple IC CODEC as the solution. There are some all-in-one USB audio chips available, but they fall short on several fronts. They generally limit you to the use of 48kHz, 16-bit audio, but more importantly, they generally have quite high distortion figures of around 0.1%, with signal-to-noise ratios topping out at about 85dB. We need better performance than that.

The first prototype for this project used the same analogue-to-digital converter (ADC) and digital-to-analogue converter (DAC) boards from the *DSP Active Crossover* (Jan-Mar 2020).

Those boards use the Cirrus Logic CS5381 and CS4398 chips respectively.

While they are a few years old, their performance is phenomenal. The CS4398 DAC has a dynamic range of 120dB and signal-to-noise ratio (SNR) of 107dB; the CS5381 ADC achieves an SNR of 110dB, or 0.0003%.

So we decided to stick with those chips but put as much as possible onto one board, to make it easier to build and give a nice, compact result. The performance this USB sound card delivers should fulfil even the most ardent Hi-Fi enthusiasts' desires.

We did make several changes and improvements compared to that earlier project, though. This design teases the maximum performance from these parts, in a 'no-compromise' approach to low noise and low distortion.

Plus, it provides 'plug-and-play' operation for Windows, Mac and Android computers. We tested it on

Windows, but trust the vendor's promise of Mac and Android compatibility.

During the development process, we made several key decisions:

- To get the best performance, we need to isolate the PC's ground from the USB sound card. Computers are noisy things, so we must break the ground loop.
- It must be supported by proper drivers in Windows and ideally, all other common operating systems.
- The ability to handle different sampling rates is important, though once set, it will generally be left alone.
- The PCB layout must minimise noise, plus we need to be able to connect the inputs and outputs in a variety of ways.
- Putting a transformer in the box would introduce measurable 50Hz related noise, even if we took measures to minimise it. Since we don't want a complicated power supply arrangement, we chose a DC plugpack.
- For the neatest/cleanest project for *PE* constructors, everything should be on one PCB.

As we have noted in the past, the use of some surface-mount components is unavoidable in projects like this. We need to use specific parts to get this level of performance, and in many cases, they only come in SMD versions. In this case, that includes the USB interface and the ADC and the DAC chips.

Where possible, though, we have used through-hole components. This has resulted in the PCB being a bit larger than an all-SMD version would be, but we have found a very nice case that fits it neatly.

Principle of operation

Fig.1 shows the block diagram of the *SuperCodec*. It consists of a USB-to-I²S (serial digital audio) interface with galvanic isolation to the remainder of the circuit, a local clock generator for

Features

- Stereo input and output with very low distortion and noise
- Connects to computer via USB
- Windows, macOS and Android driver support
- Asynchronous sampling rate conversion (completely transparent)
- Full galvanic isolation between computer and audio connectors
- Housed in a sleek aluminium instrument case
- Power by 12V DC (eg, from plugpack)
- Power and clipping indicator LEDs.

the ADC and DAC with bidirectional asynchronous sampling rate conversion (ASRC), the power supply section and the aforementioned ADC and DAC sections.

We have chosen to use a MiniDSP MCHStreamer to provide the USB interface. This is a pre-built device that we have integrated into our design.

This avoids us having to develop the hardware and USB driver software for the PC which is complex, expensive and needs to be done very well to deliver you an easy-to-use product.

It is essential that constructors can reliably install the sound driver software for this project and have it work with a minimum of fuss. The investment in this component is well worth the ease of use it will deliver for you.

This project appears to a Windows computer as a sound interface that you select and use just like any other – we show you how to in the box titled *Setting up the MCHStreamer*. This is essentially a regular audio device then, just one of very high quality.

The MCHStreamer is a very clever device that can provide 10 input and output channels (five stereo pairs) with sampling rates of 32-384kHz at 24 bits. It supports I²S as well as TDM and other audio formats.

We are using it as a two-channel (stereo) audio interface. This leaves many channels unused, but that is not the aim of this project. If you want to use this design as the basis of a multi-channel recorder, be our guest!

The MCHStreamer is powered from the USB cable and breaks out the I²S audio interface that we need on a pair of headers.

The chip we're using for galvanic isolation requires a power supply on both sides of the barrier. Luckily, the MCHStreamer has a 3.3V output available on an expansion header which we can use to power the computer-side of that chip. The audio-side power supply is derived from the plugpack, along with power for the rest of the circuit.

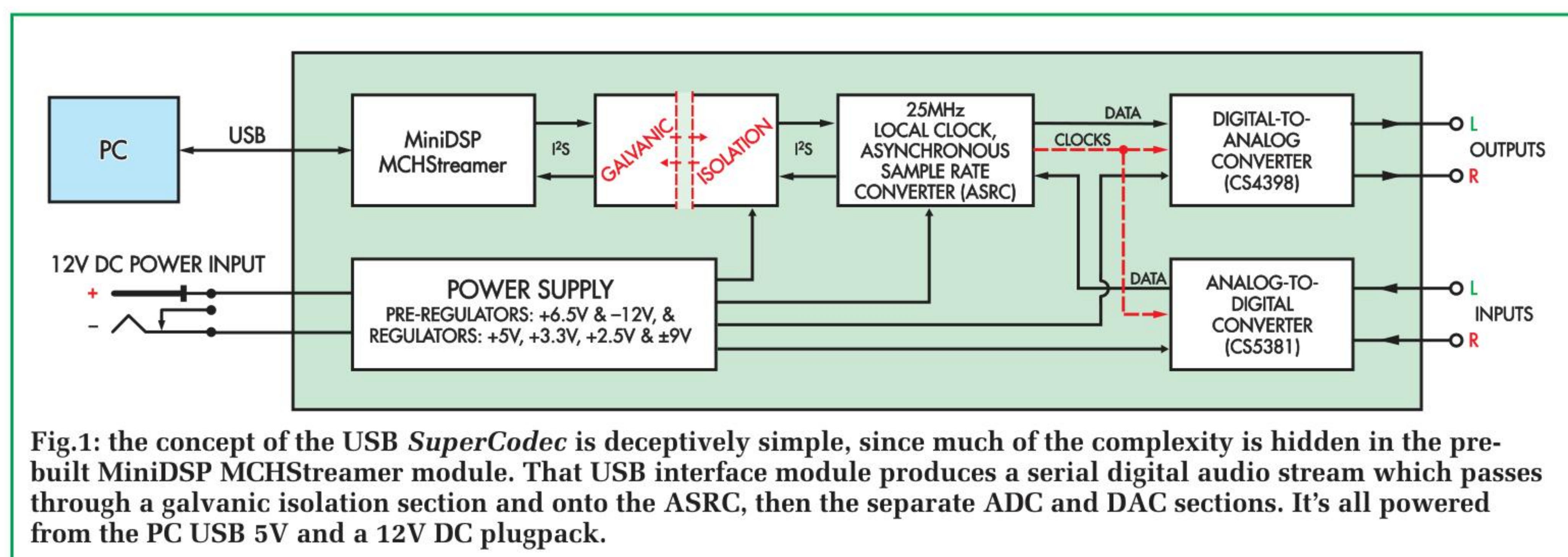
You can buy the MCHStreamer from: <https://bit.ly/pe-sep21-mch> – once you register and order it, you can download the PC driver software.

We have laid out our sound card so that the MCHStreamer plugs straight onto the underside of the board. This avoids having to send high-speed digital signals over a ribbon cable. When purchasing parts for this, be very careful to get the header specified in the parts list. Any alternative needs a pin pitch of 2mm and a minimum height of 10mm; otherwise, you will not be able to seat the MCHStreamer fully.

Performance measurements

We used three methods to measure the performance of the USB *SuperCodec*, and these measurements aided us in improving it over several iterations until we arrived at the final design.

The first method was to feed in a very-low-distortion sinewave from a



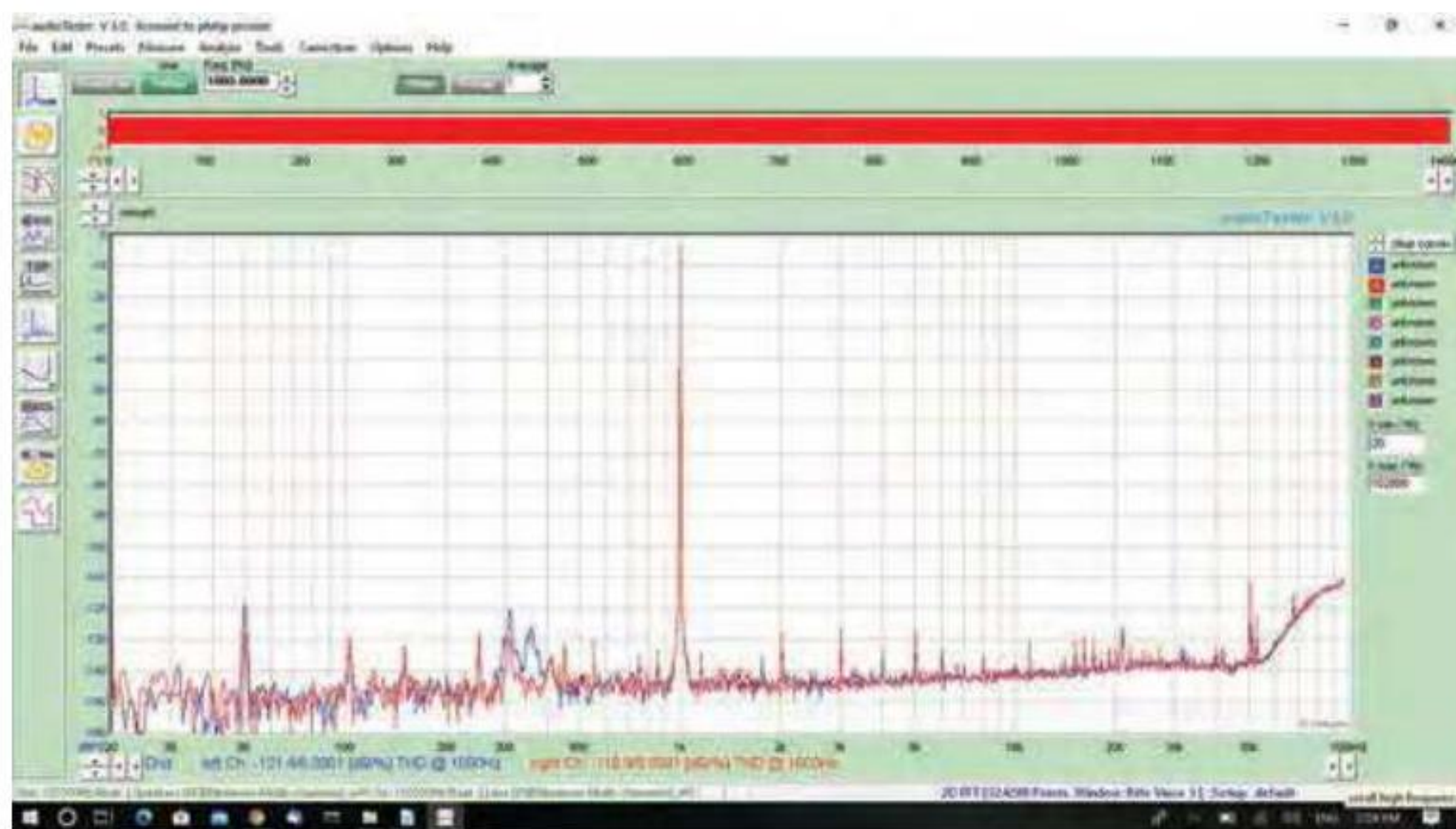


Fig.2: spectral analysis (large window FFT) of the data from the *SuperCodec*'s ADC when fed a sinewave from a Stanford Research Ultralow Distortion Function Generator. This gives an excellent result of 0.0001% THD (−121.4dB). That's despite an earth loop causing a larger-than-normal spike at 50Hz, which was fixed with some extra isolation in the final version of the sound card.

Stanford Research DS360 Ultralow Distortion Function Generator. Very large sample sets were run through an FFT so we could inspect the close-in phase noise.

The reason for doing this (rather than merely looping the output back to the input) is that we need independent clocks for the signal generator and ADC to pick up any distortion caused by clock jitter. With both devices running off the same clock, those effects are liable to cancel each other out, at least partially.

The results of this first test are shown in Fig.2. Note that we had an earth loop during this test, leading to a greater than usual spike at 50Hz (this was fixed later); despite this, the reading is extremely promising with a THD figure of just 0.0001% (−118dB) THD.

To verify that clock jitter is not a problem, we then 'zoomed in' to the 1kHz fundamental, as shown in Fig.3.

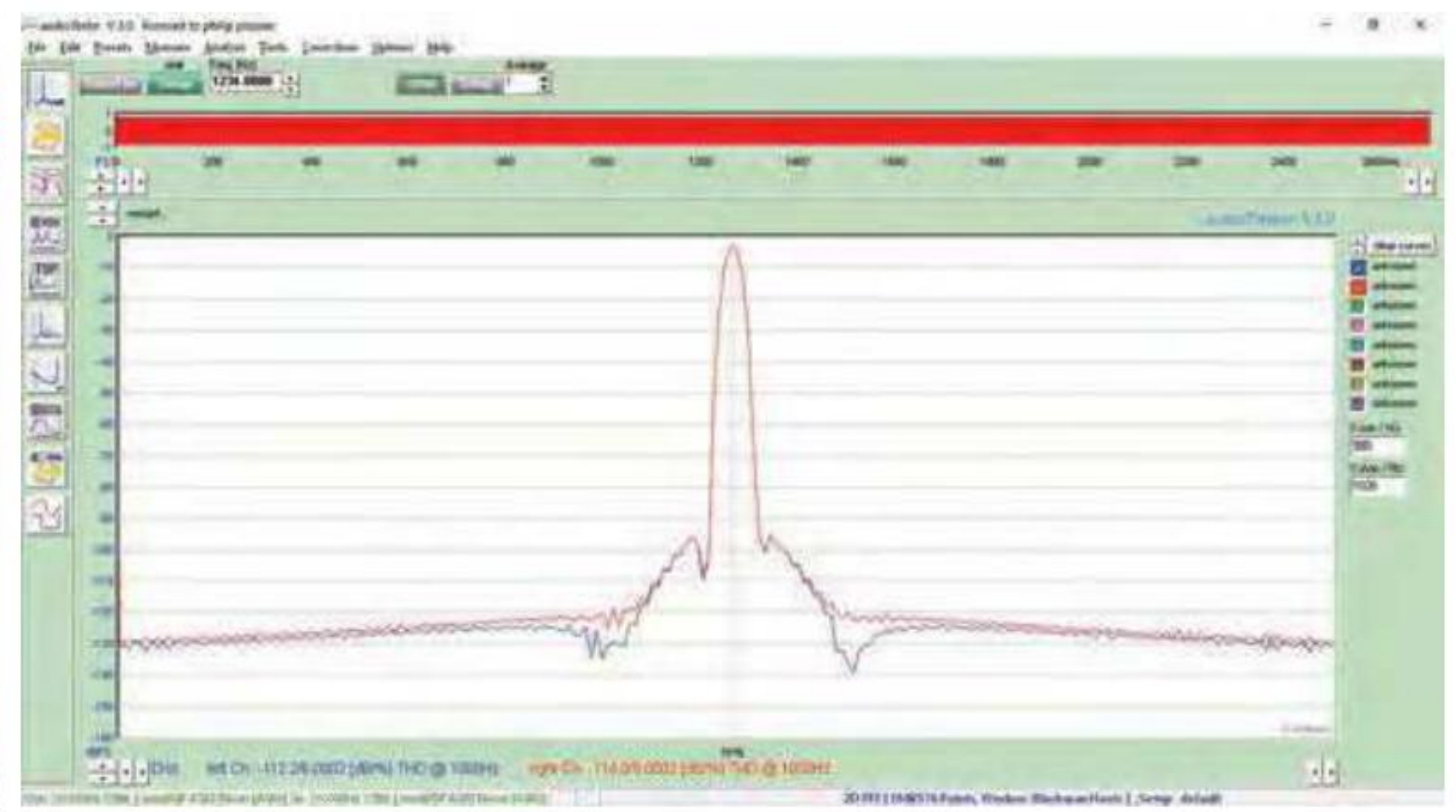


Fig.3: a close-up of the 980-1020Hz portion of the spectral analysis, showing very little evidence of clock jitter in the ADC system. That's because the crystal oscillator, digital isolators and ASRCs are all low-jitter devices. High jitter can distort signals since the sampling rate effectively changes between samples.

Specifications

- Sampling rate: 32-192kHz
- Resolution: 16-32 bits (24 bits actual)
- Loopback total harmonic distortion (THD): 0.0001% (−120dB)
- DAC THD+N: 0.00050% (−106dB)
- ADC THD+N: 0.00063% (−104dB)
- Loopback THD+N, no attenuator: 0.00085% (−101.4dB)
- Loopback THD+N, 8dB resistive attenuator: 0.00076% (−102.5dB)
- Recording signal-to-noise ratio (SNR): 110dB
- Playback SNR: 107dB
- Dynamic range: 120dB
- Input signal level: up to 1V RMS
- Output signal level: up to 2.4V RMS; 2.0-2.2V RMS (−1.5 to −0.75dB) for best performance

Loopback testing

The second test method was to connect the unit's outputs to its inputs via a stereo RCA-RCA cable. This lets us conduct 'loopback' tests using PC audio analysis software. The result of the first such test is shown in Fig.4. You can see that we've solved the earth loop now as the 50Hz peak is at −130dB! You can also see the 50kHz spike from the switch-mode circuitry.

Importantly, there is no spike at 25kHz, 12.5kHz or related frequencies, suggesting that the switchmode

regulators are not squegging – ie, are free from subharmonic oscillation that could affect audible frequencies.

The harmonics of the very slightly distorted 1kHz fundamental are visible at 2kHz, 3kHz... up to 8kHz, then 11kHz and 12kHz. The strongest harmonic is 2kHz (second harmonic), at

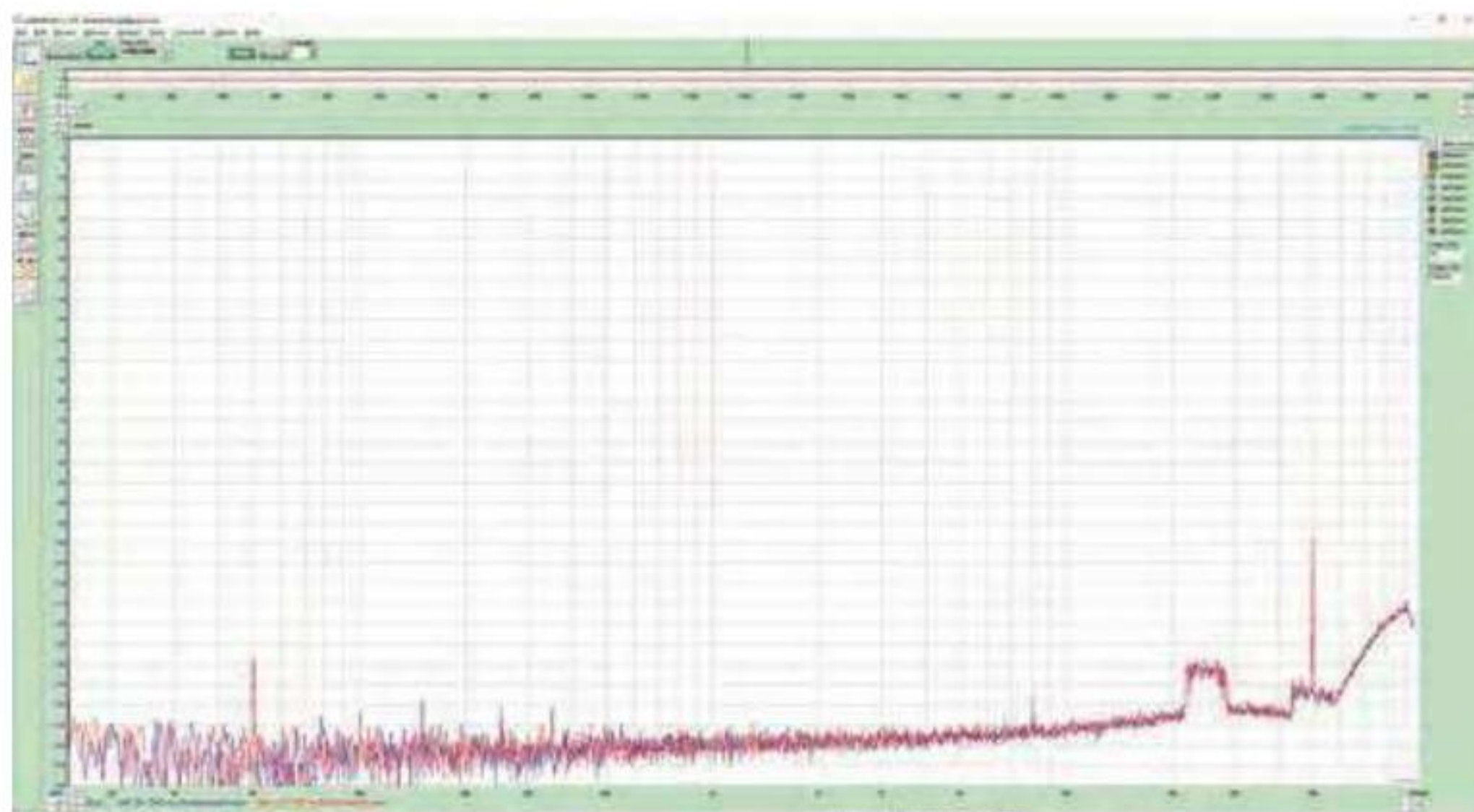


Fig.6: the noise floor of the complete DAC+ADC system. Although it is higher than the ADC alone, it is still very low at around −130dB.

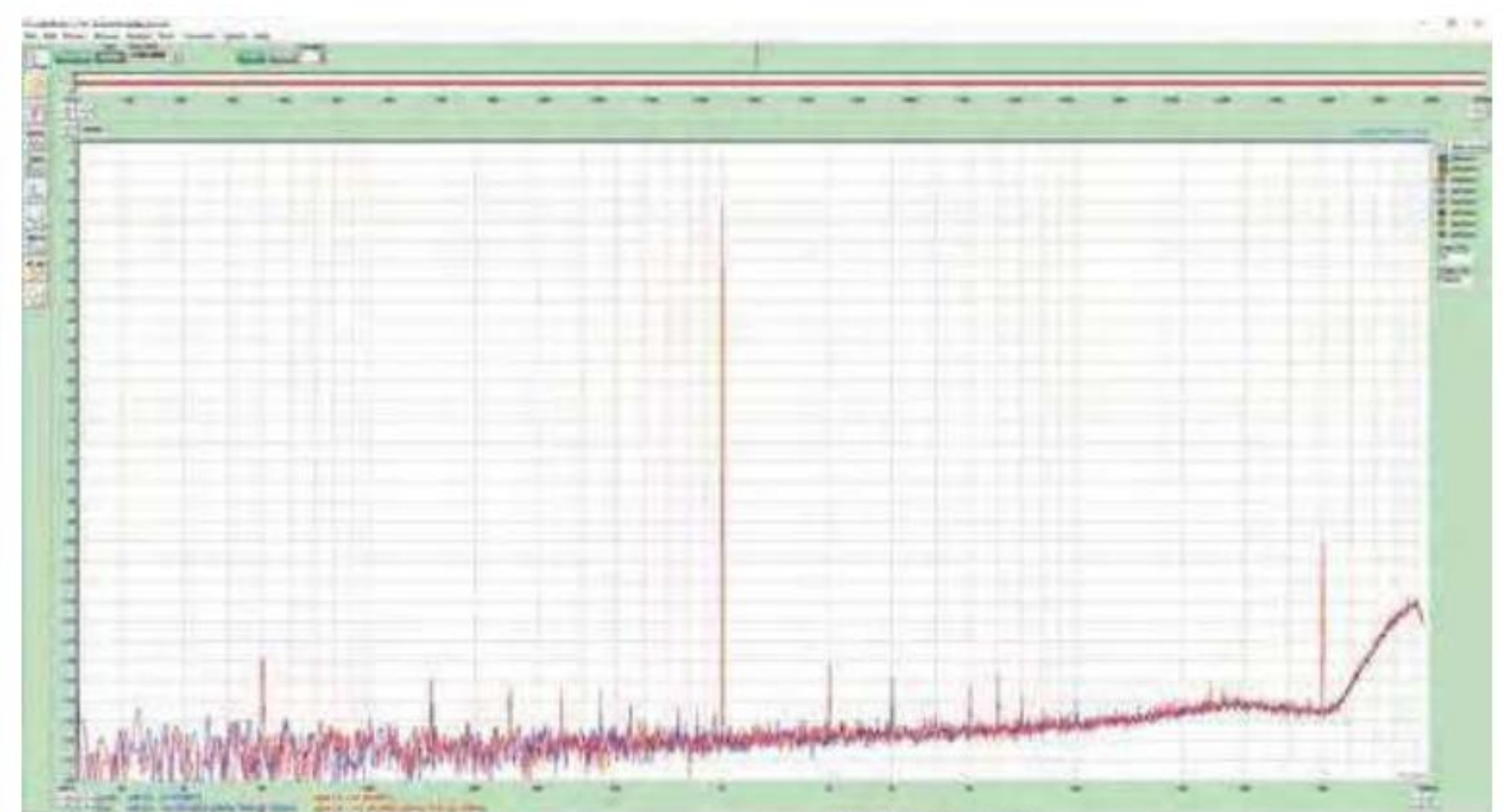


Fig.7: here the 1kHz test signal has been reduced in amplitude by 10dB, dropping from around 1V RMS to around 0.1V (100mV) RMS. That's below most normal 'line level' signals, but despite this, distortion performance is still excellent, with THD measuring as −112dB/0.0002%.

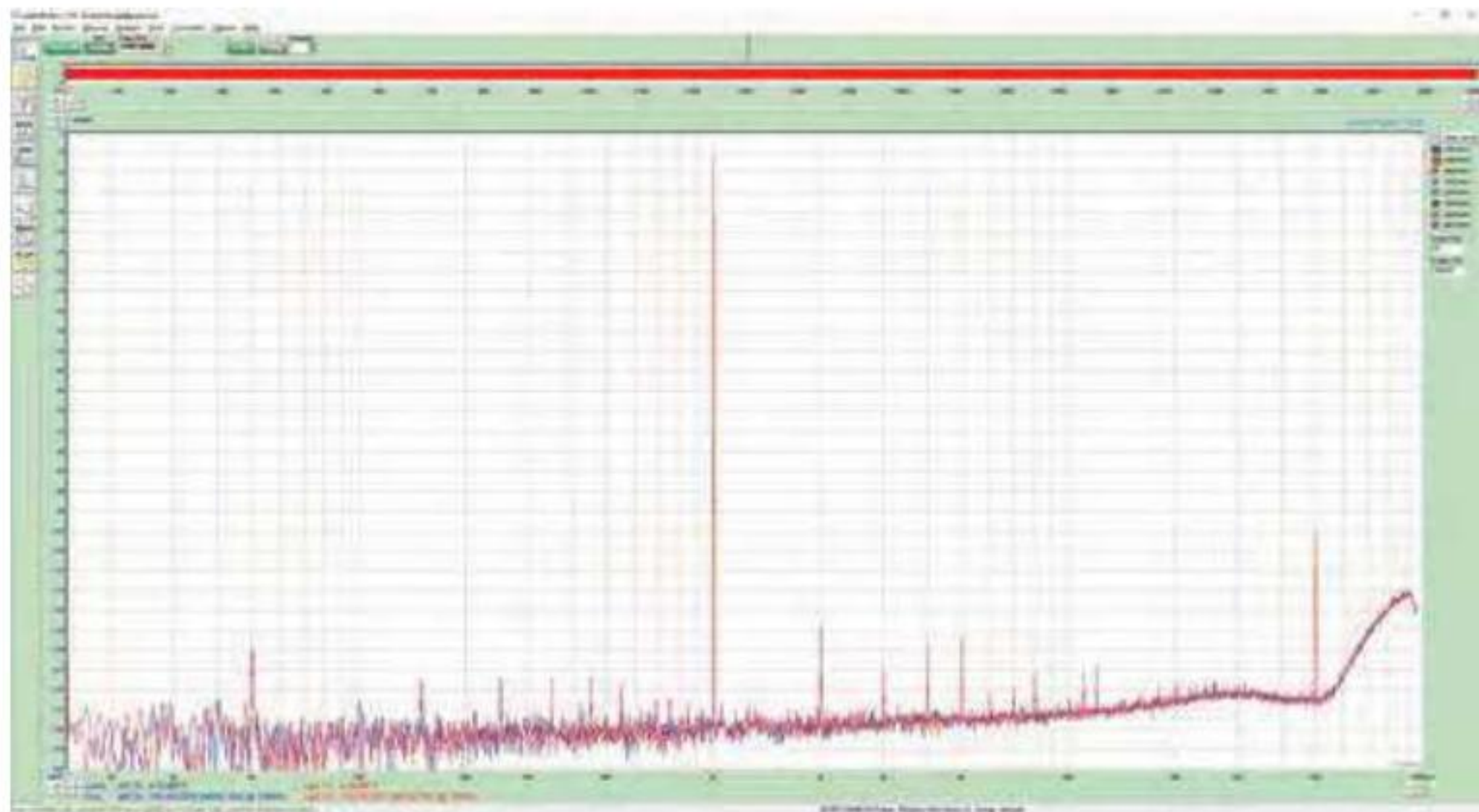


Fig.4: the first loopback test, measuring the performance of the complete DAC+ADC system. Performance is still excellent with only slightly higher harmonic distortion than the ADC alone, at -118dB (still rounding to 0.0001%).

around -118dB . The result is a very low THD figure of $-118\text{dB}/0.00013\%$. Remember, that this now includes any distortion from the DAC plus the ADC, so this is very impressive. But this measurement does not include noise.

To calculate the THD+N figure and signal-to-noise ratio, the inputs to the ADC were shorted out, and a new spectrum captured (Fig.5). We then reinstated the loopback cables and measured the input level with the DAC silent (Fig.6). These give us an idea of the noise floor, which is around -104dB for the ADC alone and -102dB for the DAC+ADC. Both figures are limited by 50Hz hum pickup.

Since these levels are significantly higher than the THD alone, that means the THD+N performance figures for the sound card are determined just by the noise levels.

By the way, since the DAC has to have its output level set no higher than -7.5dB to avoid overloading the ADC in the loopback test, we could have gotten better results by inserting a resistive divider between the output and input.

Indeed, if you are using this device as part of a measurement system, you would need resistive dividers, especially if the device you are measuring has gain (eg, an audio amplifier).



The back end of the SuperCodec has all the input and output connectors (the RCA sockets) along with the USB connector and the 12V DC power socket.

So when used as a measurement system, expect slightly better performance than the figures given here suggest. Essentially, the loopback THD+N (and thus the measurement limit) will approach the 0.00063% (-104dB) figure given for the ADC alone.

We made many other loopback measurements at other test frequencies ranging from 20Hz up to 19kHz , all with virtually identical results, so the plots are not worth reproducing. We also ran 1kHz tests with lower and higher signal levels.

Fig.7 shows the results with the output level reduced by 10dB . This only increases the THD figure to $-112\text{dB}/0.0002\%$, indicating that you aren't sacrificing much performance by operating the codec at lower signal levels when necessary.

Fig.8 is at the maximum output signal level, which increases second and third-harmonic distortion so that the THD figure is $-111\text{dB}/0.0003\%$. This indicates that the optimal signal level for low distortion is a few decibels below maximum.

But you'll still get decent results at the maximum output signal level, if that's what you need.

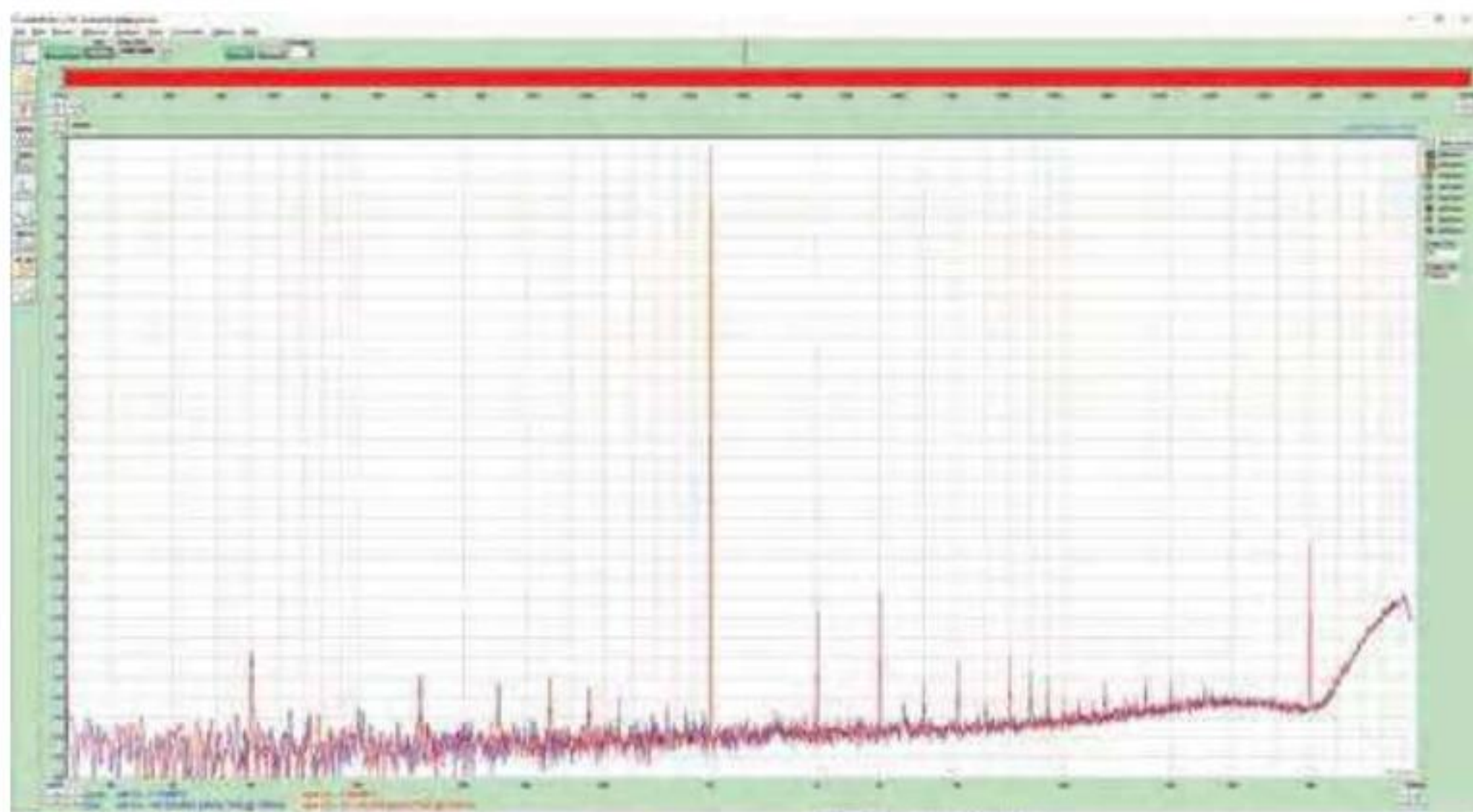


Fig.8: the 1kHz test signal has been increased to the maximum DAC output level of a bit more than 2V RMS . You can see that in this case, more isn't necessarily better, as the THD figure is slightly worse than the 1V test case, yielding a THD figure of $-111\text{dB}/0.0003\%$. That's still excellent, though!

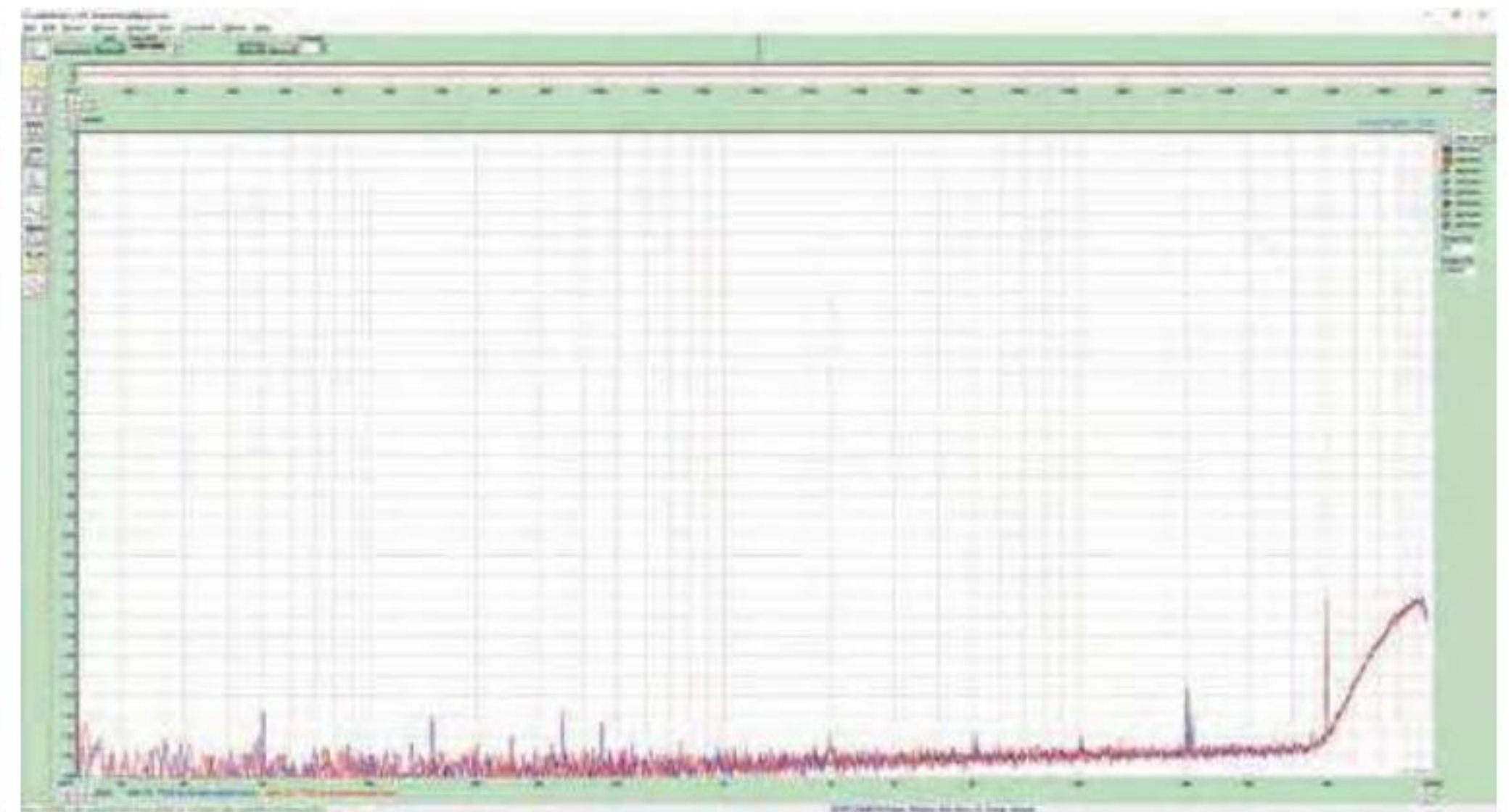


Fig.5: the noise floor of the ADC, measured with the inputs shorted. The biggest spike in the audible range is at 50Hz due to mains hum pickup, but this is hardly a problem, being below -140dB .

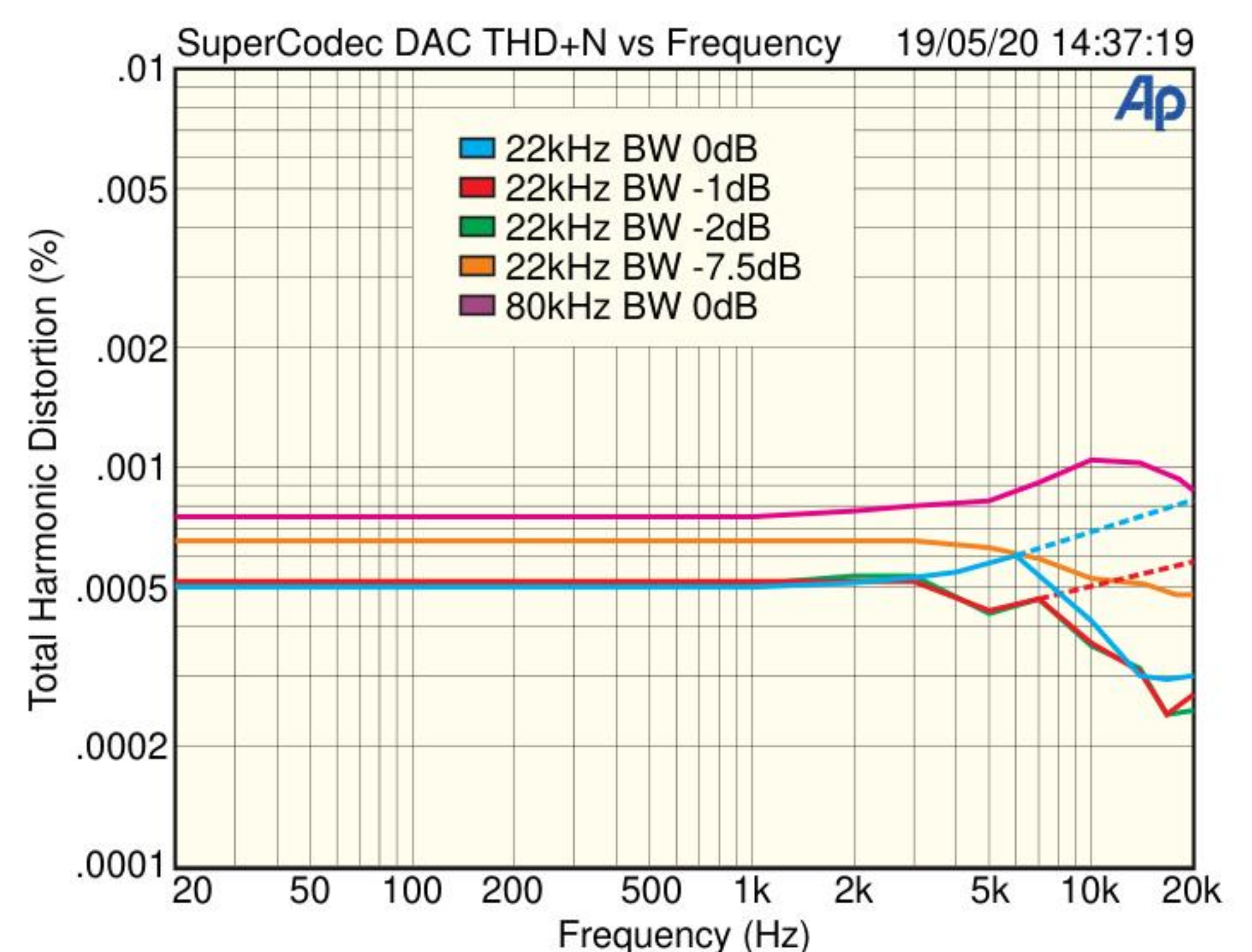


Fig.9: THD+N (not THD) at four different signal levels for the SuperCodec's DAC, as measured with our Audio Precision System Two. The fifth curve has a wider measurement bandwidth of 20Hz - 80kHz , to get a more realistic idea of distortion levels at higher frequencies. Unfortunately, measurements with 80kHz bandwidth also have an unrealistically high noise level.

Parts list – USB SuperCodec

- 1 PCB assembly – see below
- 1 Hammond 1455N2201BK extruded aluminium instrument case with black panels [Altronics H9125, Mouser 546-1455N2201BK]
- 1 MiniDSP MCHStreamer USB-to-I²S interface [https://bit.ly/pe-sep21-mch]
- 1 12V DC plugpack, 1.5A+ [Altronics M8936D, Jaycar MP3486]
- 2 white (or black) insulated panel-mount RCA sockets (CON6a,CON7a) [Altronics P0220, Jaycar PS0496]
- 2 red insulated panel-mount RCA sockets (CON6b,CON7b) [Altronics P0218, Jaycar PS0495]
- 2 plastic TO-220 insulating bushes
- 2 M3 x 6mm panhead machine screws
- 1 M3 x 10mm panhead machine screw
- 2 M3 flat washers
- 3 M3 shakeproof washers
- 1 M3 hex nut
- 2 3mm inner diameter solder lugs
- 2 3mm inner diameter fibre washers
- 1 8mm tall adhesive rubber foot [Altronics H0930, Jaycar HP0825]
- 4 12mm round slim adhesive rubber feet [Altronics H0896]
- 1 1m length of heavy-duty figure-8 shielded audio cable [Altronics W2995, Jaycar WB1506]
- 1 30cm length of 2.4-3mm diameter black or clear heatshrink tubing
- 1 30cm length of 5mm diameter black or clear heatshrink tubing

PCB assembly parts

- 1 double-sided PCB coded 01106201, 99.5 x 247.5mm
- 1 150µH 5A toroidal inductor (L1) [Altronics L6623]
- 2 47µH 0.5A bobbin-style inductors (L2,L4) [Altronics L6217]
- 1 100µH 5A toroidal inductor (L3) [Altronics L6622, Jaycar LF1270]
- 13 4-5mm ferrite suppression beads (FB1-FB13) [Altronics L5250A, Jaycar LF1250]
- 2 M205 fuse clips (F1)
- 1 5A fast-blow M205 fuse (F1)
- 3 16x22mm TO-220 PCB-mount heatsinks (HS1-HS3) [Altronics H0650, Jaycar HH8516]
- 1 PCB-mount DC barrel socket, 2.1mm ID (or to suit plugpack) (CON1) [Altronics P0620, Jaycar PS0519]
- 2 tall 6x2-pin header sockets, 2.0mm pitch (CON2,CON3) [Samtec ESQT-106-03-F-D-360; available from Mouser]
- 2 4-pin polarised headers with matching plugs, 2.54mm pitch (CON4,CON5) [Altronics P5494+P5474+P5471, Jaycar HM3414+HM3404]
- 3 mica or rubber TO-220 insulating washers
- 3 plastic TO-220 insulating bushes
- 3 M3 x 6mm panhead machine screws
- 3 M3 flat washers
- 3 M3 shakeproof washers
- 3 M3 hex nuts
- 1 60 x 70mm rectangle of Presspahn, Elephantide or similar insulating material

Semiconductors

- 1 CS5381-KZZ stereo 192kHz ADC, TSSOP-24 (IC1) [#]
- 7 NE5532AP or NE5532P dual low-noise op amps, DIP-8 (IC2-IC5,IC8,IC10,IC11)
- 2 CS8421-CZZ stereo audio sample rate converters, TSSOP-20 (IC6,IC7) [#]
- 1 CS4398-CZZ stereo 192kHz DAC, TSSOP-28 (IC9) [#]
- 1 MAX22345SAAP+ 4-channel high-speed digital isolator, SSOP20 (IC12) [#]
- 1 DS1233A-10+ 3.3V supply supervisor, TO-92 (IC13) [#]

- 1 4N28 optocoupler, DIP-6 (OPT01) [Altronics Z1645]
- 1 ACHL-25.000MHZ-EK 25MHz clock oscillator module (XO1) [#]
- 2 LM2575T-ADJG 1A buck regulators, TO-220-5 (REG1,REG2) [#]
- 3 LM317T 1A positive adjustable regulators, TO-220 (REG3,REG6,REG8) [Altronics Z0545, Jaycar ZV1615]
- 1 LM337T 1A negative adjustable regulator, TO-220 (REG4) [Altronics Z0562, Jaycar ZV1620]
- 1 LP2950ACZ-3.3 100mA 3.3V low-dropout regulator, TO-92 (REG5) [Altronics Z1025]
- 1 AZ1117H-ADJ 1A adjustable low-dropout regulator, SOT-223 (REG7) [Altronics Y1880]
- 1 BC547 or BC549 100mA NPN transistor (Q1)
- 2 high-brightness 5mm LEDs (LED1,LED2)
- 9 1N4004 400V 1A diodes (D1,D22-D29)
- 2 1N5822 40V 3A schottky diodes (D2,D3)
- 12 BAT85 30V 200mA schottky diodes (D5-D16) [Altronics Z0044]

Capacitors

- 1 2200µF 25V low-ESR electrolytic [Altronics R6204, Jaycar RE6330]
- 1 2200µF 10V low-ESR electrolytic [Altronics R6238, Jaycar RE6306]
- 4 470µF 25V low-ESR electrolytic [Altronics R6164, Jaycar RE6326]
- 1 470µF 6.3V low-ESR organic polymer electrolytic [Panasonic 6SEPC470MW] [#]
- 1 220µF 25V low-ESR electrolytic [Altronics R6144, Jaycar RE6324]
- 4 100µF 25V low-ESR electrolytic [Altronics R6124, Jaycar RE6322]
- 8 47µF 50V low-ESR electrolytic [Altronics R6107, Jaycar RE6344]
- 1 33µF 25V low-ESR electrolytic [Altronics R6084, Jaycar RE6095]
- 4 22µF 50V bipolar electrolytic [Altronics R6570A, Jaycar RY6816]
- 14 10µF 50V low-ESR electrolytic [Altronics R6067, Jaycar RE6075]
- 1 1µF 63V electrolytic [Altronics R4718, Jaycar RE6032]
- 2 1µF 25V X7R SMD ceramic, 2012/0805 size [Vishay VJ0805Y105KXXTW1BC or VJ0805Y105KXXTW1BC] [#]
- 1 220nF 63V MKT
- 19 100nF 63V MKT
- 17 100nF 25V X7R SMD ceramic, 2012/0805 size [Kemet C0805C104M3RACTU] [#]
- 4 22nF 63V MKT
- 7 10nF 63V MKT
- 9 10nF 50V X7R SMD ceramic, 2012/0805 size [Kemet C0805C103J5RACTU] [#]
- 2 2.7nF 100V NP0/COG SMD ceramic, 2012/0805 size [TDK C2012C0G2A272J125AA] [#]
- 4 1.5nF 63V MKT
- 8 470pF 50V NP0/COG ceramic [TDK FG28C0G1H471JNT00] [#]
- 1 220pF X7R SMD ceramic, 2012/0805 size [AVX 08052C221K4T2A] [#]
- 2 100pF NP0/COG/SL ceramic [Altronics R2822, Jaycar RC5324]
- 2 33pF NP0/COG ceramic [Altronics R2816, Jaycar RC5318]

Resistors (1/4W 1% metal film types)

- 5 47kΩ 6 10kΩ 2 5.6kΩ 4 2.4kΩ 2 1.5kΩ
- 14 1.2kΩ 3 1kΩ 4 750Ω 4 680Ω 1 560Ω
- 2 330Ω 2 270Ω 4 240Ω 2 220Ω 4 91Ω 4 10Ω
- 1 0Ω (or 0.7mm diameter tinned copper wire)

Resistors (1/10W 1% SMD types, 2012/0805 size) [#]

- 2 47kΩ 5 2kΩ 2 1kΩ 1 220Ω 1 22Ω 1 10Ω

All components marked with [#] are available from Mouser. Jaycar/Altronics references are used to provide builders outside Aus/NZ with enough information to source alternatives. Likewise, there are lots of possible vendor tips and ideas here: <https://www.siliconchip.com.au/Shop/6/5597>

Audio Precision testing

The third measurement method we used was to hook the SuperCodec up to an Audio Precision System Two (AP2) analyser. This was mainly to verify that the above results were all correct, and we weren't somehow fooling ourselves

by using the Sound card to measure its own performance. We ran three tests: one to test the DAC in isolation, one to test the ADC in isolation, and one to test the whole system.

The first test involved feeding digital sinewaves to the SuperCodec's DAC, with its outputs then fed into the AP2's

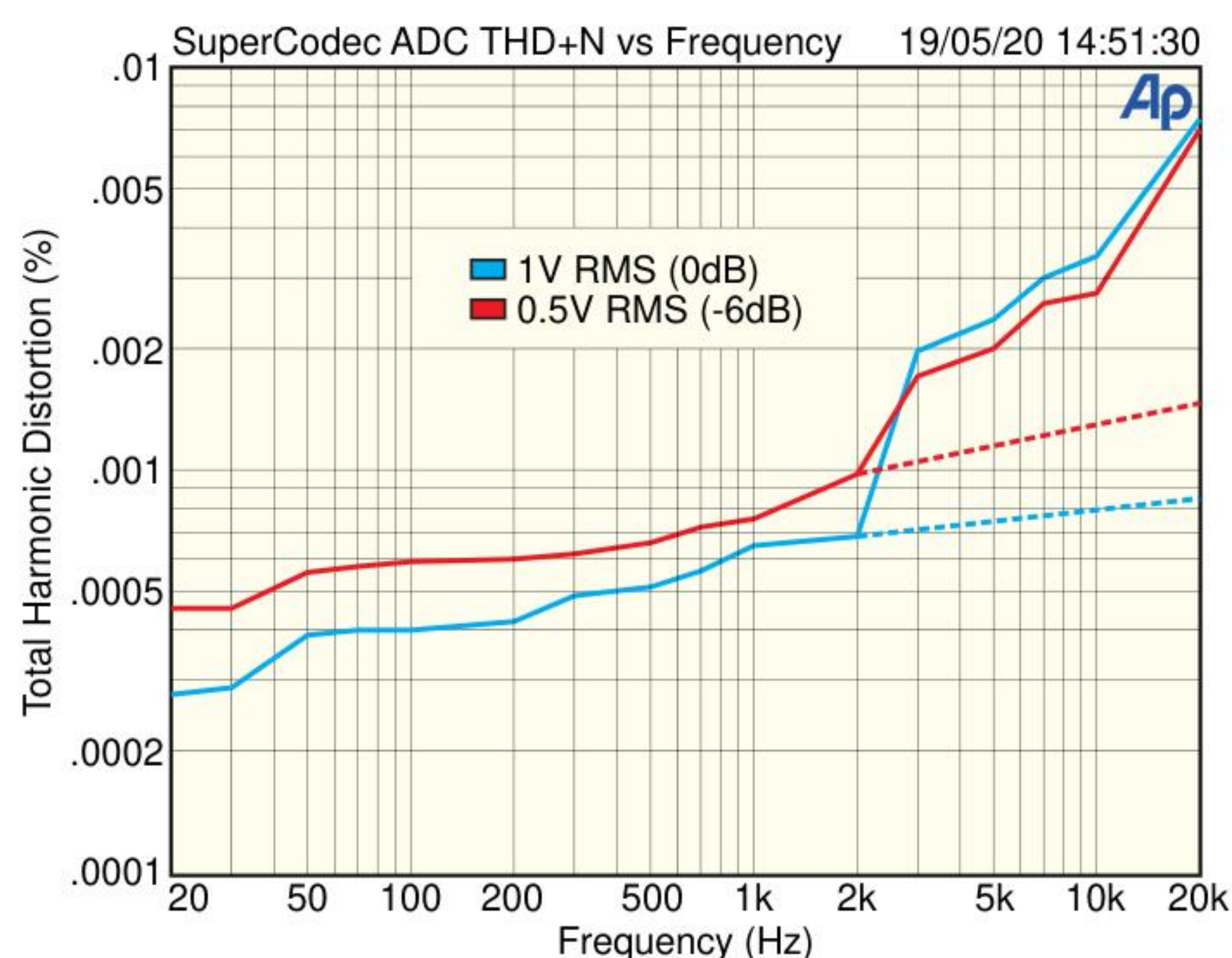


Fig.10: THD+N (not THD) at two different signal levels for the *SuperCodec's* ADC, using our Audio Precision System Two as the signal source. The rise in distortion with increasing frequency seems to be an artefact of the way the audioTester software calculates THD+N. We don't think it is a real effect. The true THD+N level for the ADC is well below 0.001% across the whole frequency range.

distortion analyser. This yielded SNR and THD+N measurements both of 106dB, and the distortion vs frequency and level plot of Fig.9.

These figures match the expected performance given in the CS4398 IC data sheet pretty much precisely, suggesting we've built the circuit correctly!

The second test involved feeding the AP2's low distortion sinewave generator into the *SuperCodec's* ADC and plotting similar curves, shown in Fig.10.

These curves are a bit 'wonky' due to the weird way that the software we used (audioTester) calculates THD+N, as we will explain in a later article. But despite this, they

confirm that the ADC performance is just slightly worse than the DAC performance, mainly to do with its lower signal levels.

The final test involved running more loopback tests, but this time using the audioTester software to measure THD+N, so that we can make a direct comparison to the Audio Precision figures. These curves are shown in Fig.11.

This time, there appears to be an artificial drop at higher frequencies, which we think can be ignored. Our assumed real performance is pretty much flat, as shown by the dashed lines.

So it seems that a measurement system based around a PC, the *SuperCodec* and some low-cost software has perfor-

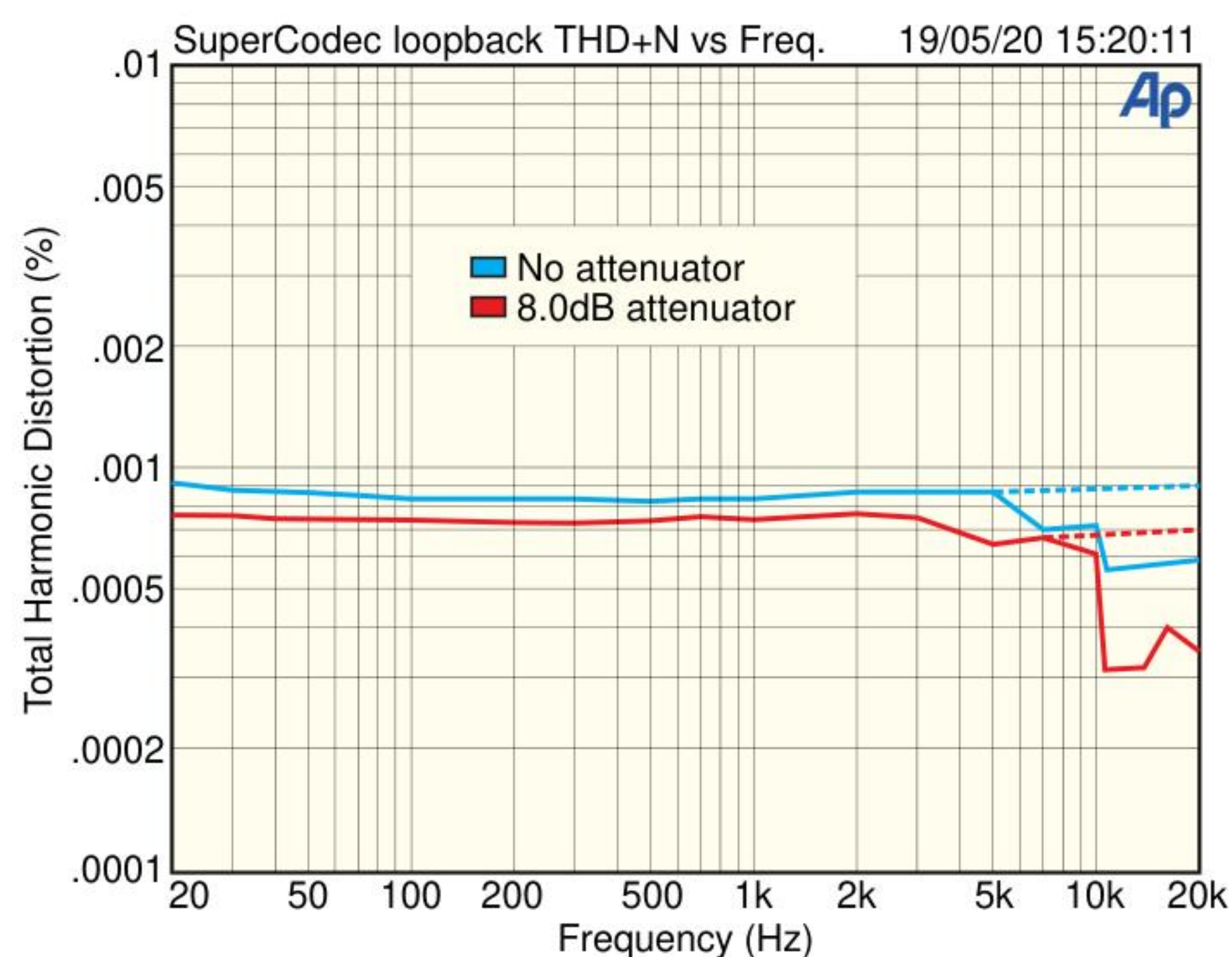
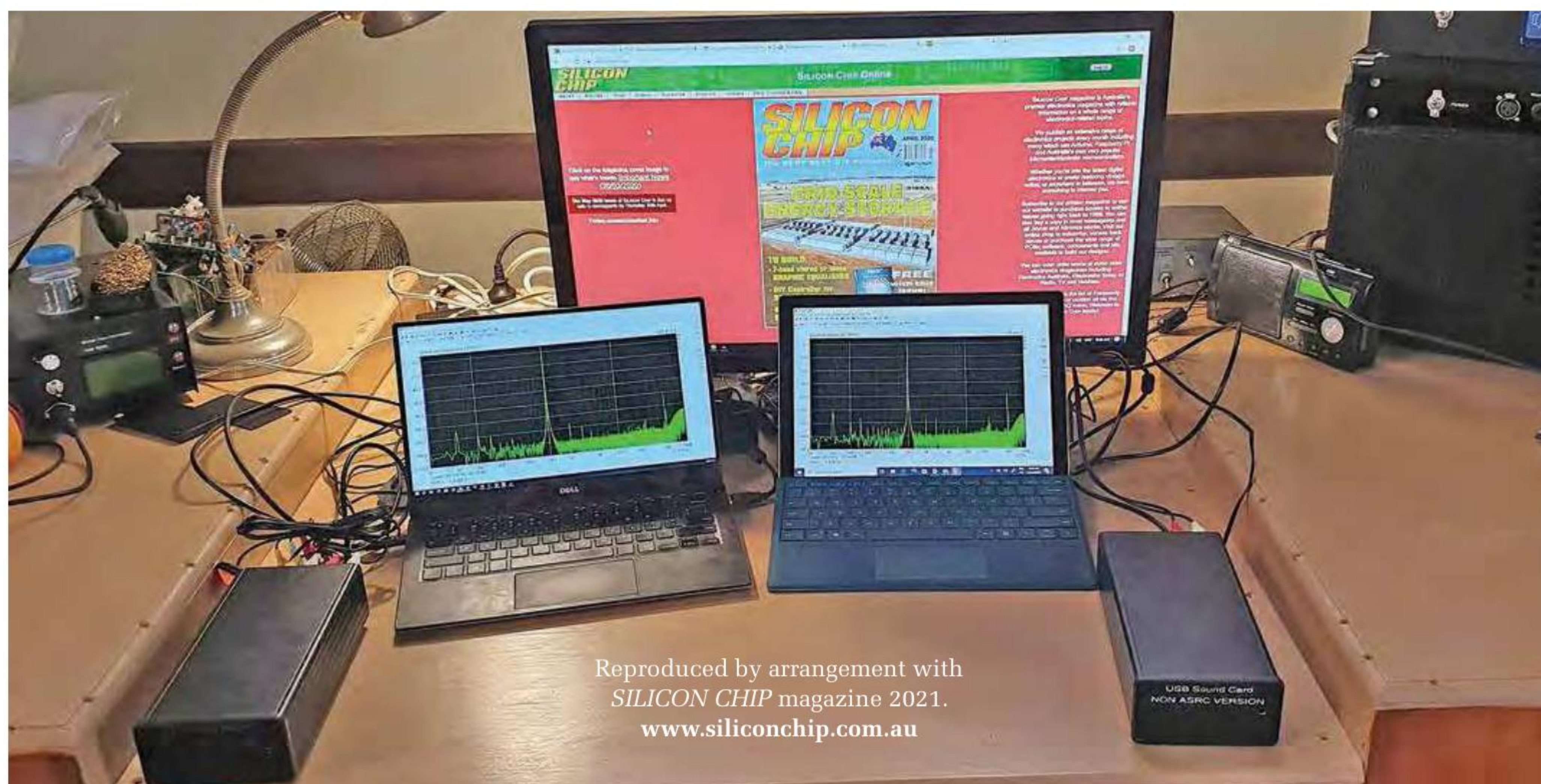


Fig.11: THD+N (not THD) calculated in a loopback manner, ie, using just the *SuperCodec* with its outputs feeding its inputs. As the nominal DAC output level is 2.4V RMS and the maximum input level is 1V RMS, its performance is best with an 8dB resistive attenuator (1.5k Ω /1k Ω) between the outputs and inputs. Otherwise, the SNR is degraded by an additional 7dB or so.

mance approaching that of our Audio Precision System Two, which cost many thousands when new. Even good used AP2s are priced at four figures. Plus, you gain additional functions and features with this solution compared to the AP2, such as THD-only measurements (rather than THD+N).

Next month

The *USB SuperCodec* circuit is fairly complicated, so we don't have enough room to describe it in this article. We'll present all the circuit diagrams next month, along with an in-depth description of how it all works. Then we'll describe how to build and test it in, along with tips on how best to use it.



Our test setup. We initially built a version of this card without the asynchronous sample rate conversion (ASRC) components, shown at right. The performance is pretty much identical but it's less flexible, so we decided to stick with the ASRC version.

by
Andrew Woodfield



Using fewer than 20 inexpensive parts, this compact little audio oscillator can fit into your shirt pocket, yet it delivers a super-accurate sinewave when and where you need it. It even fits into a snazzy 3D-printed case!

Shirt-Pocket Crystal-locked Audio DDS Oscillator

Compact, battery-powered test gear is really useful if you have to travel a lot. It can be invaluable for some professional tasks in remote places, or you can use it to work on your own projects while out and about, should the opportunity arise.

This equipment must be small, light, and inexpensive. It's all too easy for equipment to be damaged or lost.

This oscillator is equally useful around the workbench. It delivers very accurate audio tones, just like much larger and more expensive equipment.

Being battery-powered and in a small plastic case, it's easy to isolate it from the circuit being tested. That can be handy in some audio test setups.

Circuit description

The complete circuit of the audio oscillator is shown in Fig.1. It uses an Atmel ATtiny85 8-pin microcontroller, a rotary encoder with integrated push switch for output frequency selection, a compact I²C OLED display to show the selected frequency, and a crystal for accurate timing.

A few other passive components complete the design.

The ATtiny85 micro (IC1) forms the heart of the design. Its main clock is generated using a standard 8MHz crystal with two 15pF ceramic load capacitors, and its internal oscillator amplifier.

The small 64x32 pixel OLED display is used to show the

selected audio output frequency. A custom-designed font provides excellent display clarity. It connects to the ATtiny85 via a two-wire I²C bus (SDA for data and SCL for clock).

Two I²C bus pull-up resistors are typically connected to each of these I²C bus lines. Here, these resistors are inside the OLED display module, reducing the parts count.

Compatible OLED screens are made by several vendors; most data sheets give 3.3V as the maximum supply voltage. A few suppliers suggest they can run off 5V, but we're keeping it under 3.3V for wider compatibility.

A standard ATtiny85 chip will operate from 2.7V to 5.5V, according to the Atmel/Microchip data sheet, with a maximum clock speed of 4MHz at 2.7V.

However, I bench tested more than 30 devices from multiple batches and found that they will cheerfully operate down to 1.65V using either the internal or external 8MHz clock.

Therefore, I thought it reasonable to power the device directly from a battery of two regular AAA cells in series. It's a simple solution supplying a nominal 3V for the modest load current of 10mA. The battery life will vary depending on specific requirements.

The oscillator, including display, will successfully operate down to the typical end-of-life voltage of the pair of AAA batteries, around 1.8V.

Given this, you can expect about six months of intermittent use, ie, an hour or so of use every couple of days.

Rotary encoder

The rotary encoder selects the required output frequency and the tuning step size. The photo overleaf shows what a typical quadrature rotary encoder with pushbutton looks like.

The circuit arrangement used here is unusual, detecting rotary encoder rotation and button pressing with a single I/O pin on the microcontroller!

Usually, the two quadrature outputs of a rotary encoder are connected to separate pins on the microcontroller. The integrated pushbutton switch on the encoder then often demands an additional pin. That would result in the need for at least 10 pins total on the microcontroller in this application.

Instead, I have used a basic three-resistor analogue-to-digital converter (ADC) along with a noise-reducing 10nF capacitor to



Actual size of the optional 3D-printed case (including knobs) is 75 x 30 x 50mm so it will easily fit in your pocket.

connect all three switches internal to the rotary encoder to one micro I/O pin.

The component values used are important. They ensure that the closing of any of the internal three rotary encoder switches will generate a logic high-to-low 'pin-change' interrupt on the microcontroller. This allows the use of an event-driven interrupt handler routine to quickly and efficiently update the audio oscillator frequency within the very fast 'direct digital synthesis' (DDS) software loop.

This DDS software method prevents the use of the commonly used periodic timer interrupt, which would introduce a regular and unacceptable pause in the sinewave output. The pin-change interrupt method also delivers an improved encoder response; there is no need to wait for a periodic timer to detect rotation or switch closure. The response to rotating the knob is immediate.

Oscilloscope screen grabs Scope1 and Scope2 show the resulting waveforms at pin 1 of the micro, for clockwise and anticlockwise rotation respectively. The sharply falling leading edge triggers the interrupt.

The two different waveforms which follow this leading edge for each direction of rotation are then detected by the software by sampling the analogue voltage on that pin.

The tuning step size is changed using the encoder's integrated pushbutton. Pressing this pulls pin 1 of IC1 directly to ground, below the voltages produced by encoder rotation. This allows the micro to detect the button press and switch to the next step size (1, 10, 100 or 1000Hz). The 10nF capacitor prevents switch bounce from interfering with the process of detecting encoder rotation.

Features and specifications

- Frequency range: 1-9999Hz in 1, 10, 100 or 1000Hz steps (user selectable)
- Frequency accuracy: crystal-locked to within 0.002% at 1kHz
- Output level: 0 – 1.5V peak-to-peak (0 – 530mV RMS) sinewave (3V supply)
- Total harmonic distortion (THD): less than 3%
- Display: 0.49in (12.5mm) 64 x 32 pixel OLED
- Power supply: 2 x AAA cells @ 10mA typical
- Battery life: estimated six months of intermittent use
- Enclosure: 3D-printed compact clip-together PLA clamshell or standard Jiffy box
- Size (in clamshell case): 75 x 30 x 34mm (excluding 3D-printed knobs)
75 x 30 x 50mm (including knobs)
- Weight: 75 grams (with batteries)

Sinewave generation

The audio output tone is generated using pulse-width modulation (PWM) from one of the ATtiny85's internal counter-timers, which is fed to its digital output pin 6. Its 62.5kHz modulated carrier is higher than usual with an 8MHz crystal; a tradeoff resulting in 1% higher distortion.

A simple passive 3-pole elliptical low pass filter comprising three capacitors and one inductor, after the 1kΩ resistor from pin 6, filters out the carrier from the wanted sinewave. This filter has a 40dB notch around 60kHz. This filter method reduces current consumption and the component count.

The PWM output is matched to the filter using that 1kΩ resistor. Otherwise, the low output impedance of the microprocessor pin would cause increased waveform distortion, particularly below about 1.5kHz. The filtered sinewave output voltage level of about 1.5V peak-to-peak can be adjusted using the front panel level control potentiometer, VR1.

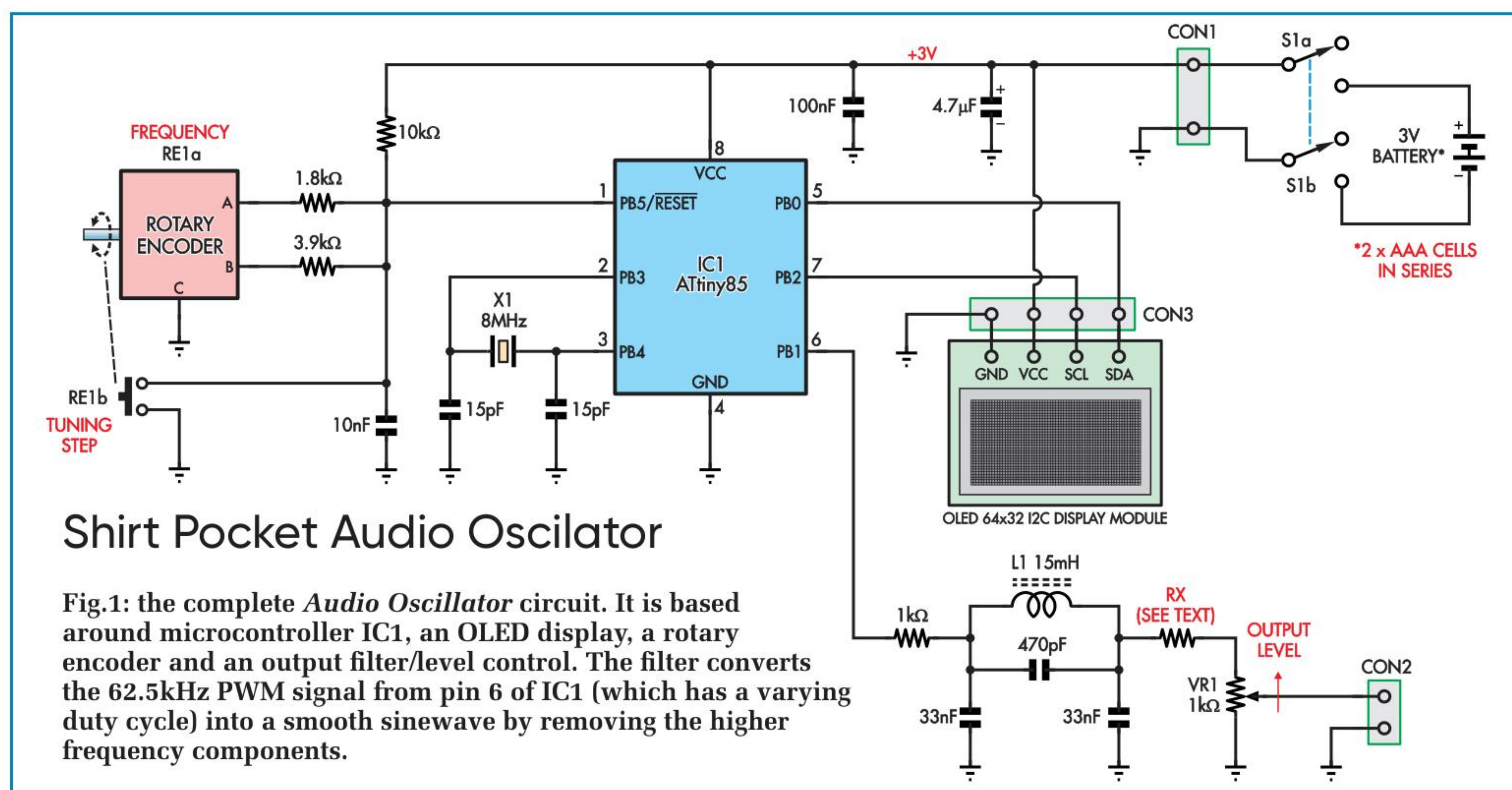
Resistor RX is optional. It may be a simple wire link if the output range is suitable for your applications, or an extra resistor can be added to reduce the maximum level. Alternatively, a two- or three-way switch and additional resistors could be added in series with the output potentiometer to provide a range of output levels, if space permits.

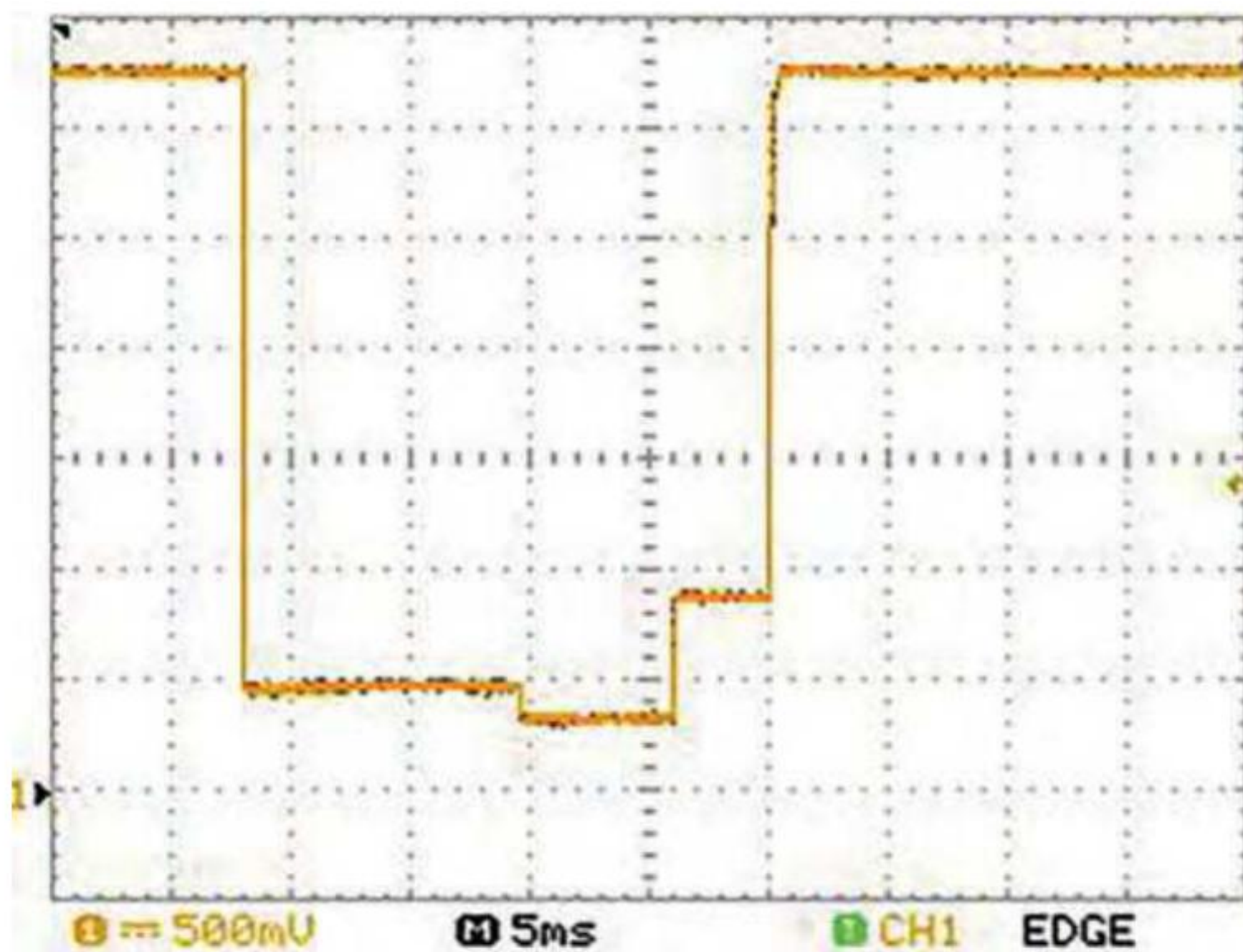
Fig.2 shows one possible arrangement using a three-way switch. Space has been provided for wiring this into the PCB using the connections for RX. The version described here does not implement this optional feature, making the finished oscillator as small as possible.

The output does not include any DC blocking capacitor. Most equipment you would feed the sinewave into will have an input capacitor. But if required, a suitable capacitor could be squeezed into the remaining space around VR1.

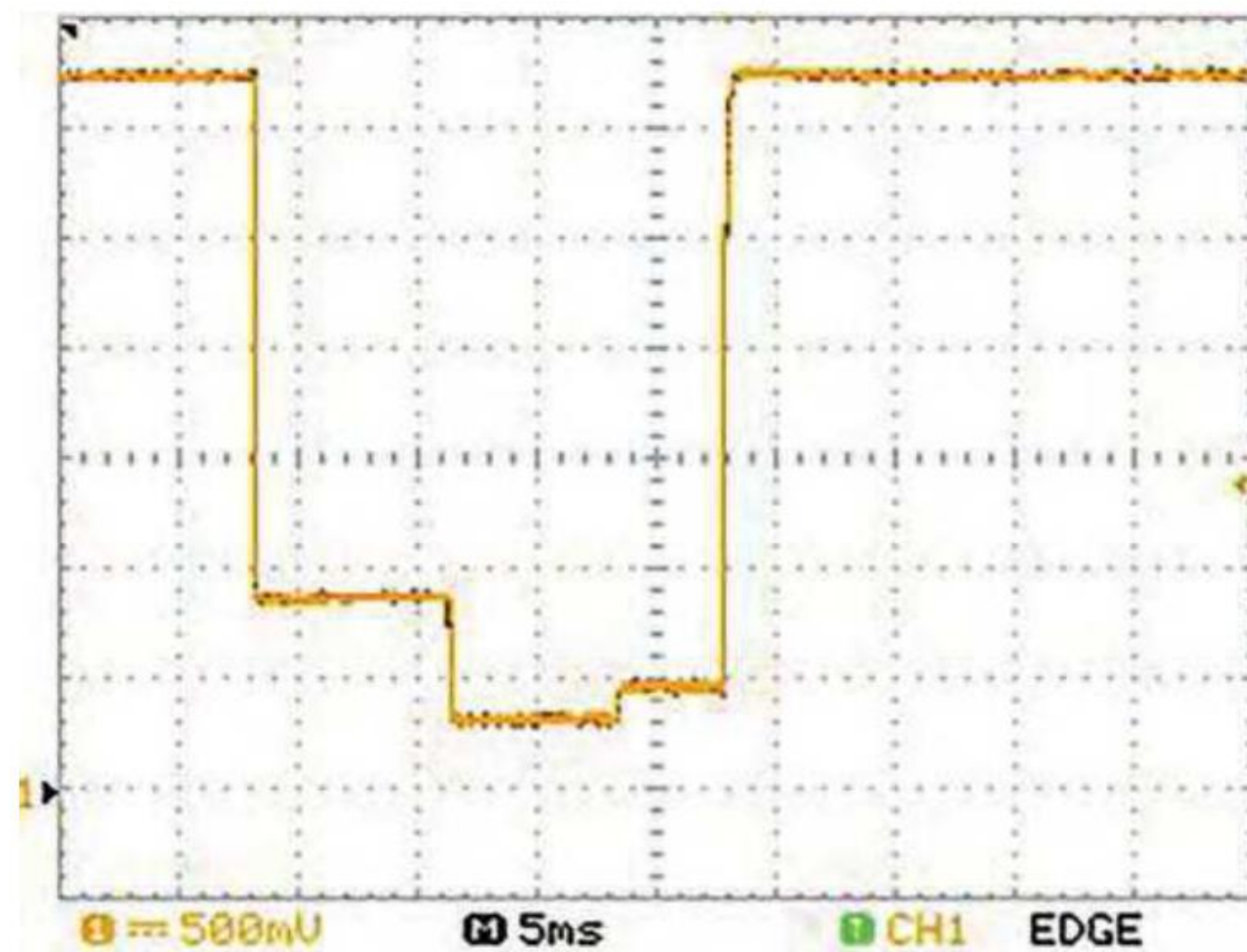
Software

The software is written using a mix of assembly code and BASCOM, the BASIC-like compiled language for





Scope1: the waveform at pin 1 of IC1 when rotary encoder RE1 is rotated one step clockwise.



Scope2: the waveform at pin 1 of IC1 when rotary encoder RE1 is rotated one step anticlockwise. It is almost a mirror image of Scope1.

the Atmel/Microchip AVR family. Assembly code is used for the core tone generating routine which must be very fast. Other sections, such as the interrupt handler code and the I²C and OLED routines, are written in BASIC as they are not so speed-critical.

The DDS lookup table contains 256 bytes of data defining the amplitude of the sinewave over time. The frequency is precisely determined by the value of the 24-bit word used to increment the DDS cycle accumulator. One byte (eight bits) of this word is used as a pointer into the sinewave amplitude data, while the other two bytes (16 bits) represent the fractional position.

The 24-bit wide accumulator ensures excellent frequency precision, along with the accurate and stable crystal-controlled processor clock.

A fast interrupt subroutine handles the rotary encoder and tuning step size selection. It looks for specific voltage changes to determine the direction of rotation, the number of turns, and the selection of tuning steps.

The interrupt routine unavoidably disrupts the output waveform briefly while the frequency change is being made. But the waveform is never going to be pure when the frequency is being adjusted anyway.

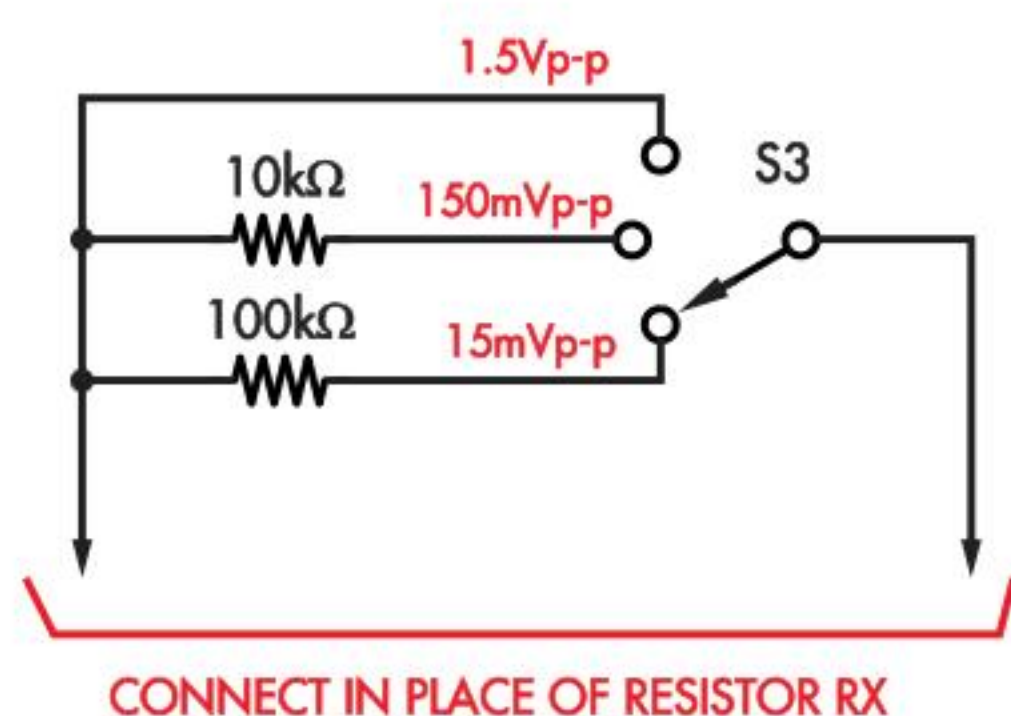


Fig.2: potentiometer VR1 allows the output level to be adjusted over the full range of 0-530mV RMS. However, if you want switchable ranges, they could easily be incorporated using a scheme like this.

Screen updates for the ultra-compact 64 × 32-pixel OLED display are sent via the I²C serial bus. The display's integrated SSD1306 controller requires careful initialisation to deliver correct operation. Its parameter settings differ significantly from those needed for the larger and more common 128 × 32 or 128 × 64 OLED displays, despite using an identical controller.

The display software also makes use of a purpose-designed character font for this display, shown in Screen1. It aims to maximise character clarity and visibility despite its size. The resulting four-digit display largely determines the frequency range of the oscillator.

Displaying frequencies of 10kHz or above accurately would require five digits. That would reduce display clarity beyond acceptable levels, particularly for those of us with reduced visual ability.

Note that smaller 0.42in (diagonal) 72 × 40 pixel OLED displays are available but oddly, they are built on a larger PCB than the 0.49-inch 64 × 32 pixel OLED display I chose! So there is little benefit in using one, but if you have one, it will work.

The software is also compatible with some, but not all, 0.96in 128 × 64 OLED displays using SSD1306 controllers. A few of these have extremely slow (faulty) I²C reset performance and will not operate correctly with this software. The software will not work with any OLED displays fitted with an alternative 'compatible' SH1106 controller.

Rotary encoder selection

The rotary encoder used in this design is critical. It must be a pulse-type rotary encoder. Unfortunately, these are visually indistinguishable from level-type encoders; worse, most suppliers will not tell you which type they are selling! Fortunately, we are selling it via the *PE PCB Service* shop.

Electrically, however, they are quite different. The two outputs on level-type encoders change at the 'click' or detent as the shaft is rotated, with the two encoder output pins remain fixed in one of the encoder's four quadrature output states when the shaft is stationary.

In contrast, pulse-type rotary encoders produce a pair of short quadrature pulses mid-click, with both encoder output pins resting open circuit. These encoders are the most commonly supplied at low cost from Asian sources. This open-circuit condition at the rest position is critical for generating the desired encoder interrupt waveforms used in this design.

These two encoder types can be quickly and easily distinguished with a continuity tester. An encoder can be tested using an ohm-meter or even an arrangement as simple as a series LED, resistor and battery as follows:

1. Connect one lead of the continuity meter to the centre pin of the three (ignore the two on the opposite side).
2. Connect the other lead to one pin on either side of the centre pin; it doesn't matter which.
3. Rotate the shaft one click.
4. Measure the continuity while the encoder is at rest.
5. Repeat steps 3 and 4 several times.

If the encoder is a pulse type, the meter should show an open circuit (very high resistance) at all rest positions. You should see a brief period of continuity (low resistance) while rotating the encoder.

If the encoder is a level type, the meter will show continuity on every second detent position and an open circuit on the other detent positions.

Last, some rotary encoders generate pulses that are opposite of others. This leads to the rotation being backwards. It can be fixed by swapping the positions of the 1.8kΩ and 3.9kΩ (A/B) resistors.

Construction

The *Pocket Crystal Audio Oscillator* is built on a PCB coded 01110201. It measures 65.5 × 24.25mm and is available from the *PE PCB Service*. As you can tell from the photos, I etched mine at home, but the commercially-made version is inexpensive.

Refer to the PCB overlay diagram, Fig.3, to see which parts go where.

For those making this single-sided PCB at home, the board may be left square if it will be fitted into a Jiffy box, or trimmed carefully along the curved PCB outline if you're making the 3D-printed enclosure.

Construction should begin by fitting the resistors and then the capacitors. The single electrolytic capacitor is the only polarised one; its longer lead goes into the pad nearest the edge of the board, marked with a '+' symbol. Also, space the 4.7µF electrolytic off the board by about 1.5mm to allow it to be bent over when inserted later into the 3D printed case.

Next, solder the crystal onto the PCB, followed by the 8-pin IC socket. Ensure that the pin 1 notch on the socket faces in the direction shown.

If you've etched the board yourself, you need to fit one insulated wire link, shown in red on Fig.3. The commercial board should have a top layer track joining these points, so you won't need to install a link.

Next, mount the four-way header socket for the display (CON3), then the 15mH moulded inductor. Follow with the rotary encoder and potentiometer.

Depending on the type of 9mm potentiometer you purchase, it may either mount directly onto the PCB or use component lead off-cuts to extend its leads to allow vertical mounting. If doing that, it would also be a good idea to glue the pot body to the board (eg, using neutral-cure silicone) as horizontal pots lack the mounting tabs of the vertical types.

Next, fit a pair of thin, 50mm-long red and black insulated stranded wires to CON1 for power. You can use a header and socket or, as I did, simply solder the wires to the PCB pads.

Similarly, connect the 300mm output twin lead to CON2. If you don't have twin lead, you could use heatshrink tubing on a pair of individual light- or medium-duty hookup wires. Do not fit anything to the other end of these wires just yet.

Programming IC1

If you have a blank micro, program it as per the box labelled, *Programming the ATtiny85*.

After programming, plug it into the socket, ensuring that its pin 1 dot lines

Parts list – Audio DDS Oscillator

- 1 PCB coded 01110201, 65.5 × 24.25mm, available from the PE PCB Service
- 1 8MHz low-profile crystal (X1) [Altronics V1249A]
- 1 ATtiny85 8-bit microcontroller, DIP-8, programmed with 0111020A.hex [Jaycar ZZ8721 or Altronics Z5105]
- 1 8-pin DIL IC socket
- 1 pulse-type rotary encoder with integrated pushbutton switch (RE1) available from the PE PCB Service
- 1 DPDT slide switch (S1) [Jaycar SS0852, Altronics S2010]
- 1 0.49in 64 × 32 I²C OLED display module [eBay, AliExpress – for example, at the time of writing eBay item 273942316375]
- 1 15mH molded radial choke (L1)
[eg, Murata 17156C (Digi-Key) or Murata 22R156C (RS)]
- 2 2-pin headers and matching sockets (CON1 and CON2; optional)
- 1 4-pin SIL header socket, ideally a low-profile type (CON3)
- 1 4-pin header (plugs into CON3; may come with OLED screen)
- 2 knobs to suit RE1 and VR1 [3D printed or Altronics H6016]
- 1 2 × AAA side-by-side cell holder (optional; see text)
[Jaycar PH9226, Altronics S5052]
- 1 pair of small alligator clips [Jaycar HM3020, Altronics P0101+P0102]
- 1 3D-printed plastic enclosure, assembled size 75 × 30mm × 34mm
(or a UB5 Jiffy box – see text)
- 1 300mm length of light- or medium-duty two-core cable
- 1 100mm length of red light-duty hookup wire
- 1 100mm length of black light-duty hookup wire
- 1 20mm length of insulated solid-core wire (eg, bell wire or breadboard jumper wire)

Capacitors

- 1 4.7µF 50V electrolytic
- 1 100nF ceramic
- 2 33nF MKT or greencap
- 1 470pF ceramic
- 1 10nF MKT or greencap
- 2 15pF ceramic

Resistors (all 1/4W 1% metal film)

- 1 10kΩ
- 1 3.9kΩ
- 1 1.8kΩ
- 1 1kΩ
- 1 1kΩ linear 9mm potentiometer (VR1) [Jaycar RP8504, Altronics R1986]

Programming Adaptor Board (optional)

- 1 PCB coded 01110202, 25.5 × 22mm, available from the PE PCB Service
- 1 8-pin DIL IC socket
- 1 3x2 pin header (CON4)
- 1 3mm red LED (LED1)
- 1 100nF ceramic capacitor
- 1 1kΩ 1/4W resistor

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up with the notch on the socket. You may need to straighten its leads to fit into the socket. Be careful not to allow any of the leads to fold up under the chip body during insertion.

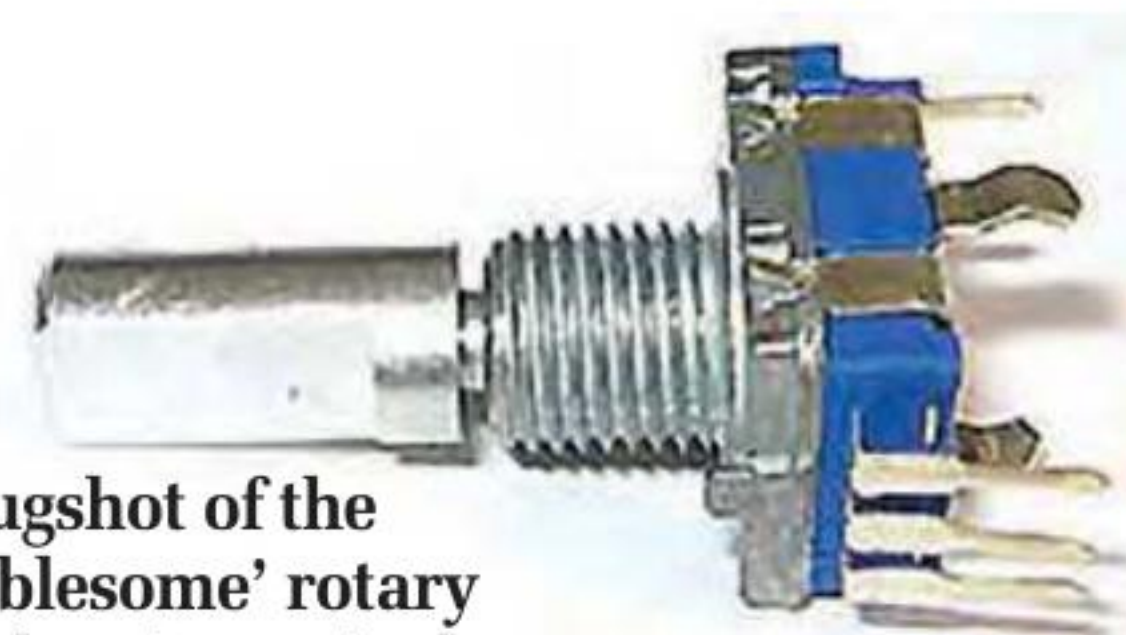
Next, plug the OLED display into its socket on the PCB. The screen is usually supplied with a four-way 0.1in-pitch header. If it has not already been fitted to the display PCB, solder it now.

Next, if you're using a standard-height header socket for CON3, use a spudger or a sharp-edged blade to carefully slide off the plastic pin separator from the pin header. Then trim the four pins shorter by about 2mm. This allows the display to fit as closely as possible to the top of the ATtiny85 chip. See the side view photo for an idea of how it plugs together.

If you were able to get a low-profile header socket for CON3, that should not

be necessary. It should just plug straight in, although you may still have to trim the header pins a little.

The PCB can now be tested. Before you connect the 3V supply, carefully check all of your soldering for shorts or missed connections. If it looks OK, connect up a 3V supply (*important:*



A mugshot of the 'troublesome' rotary encoder. Annoyingly, level-type encoders are externally indistinguishable from the pulse-type encoders that we need. Either take an educated guess about which one to order, then test it when it arrives, using the procedure described in the text... or just buy it from the *PE PCB Service* shop!

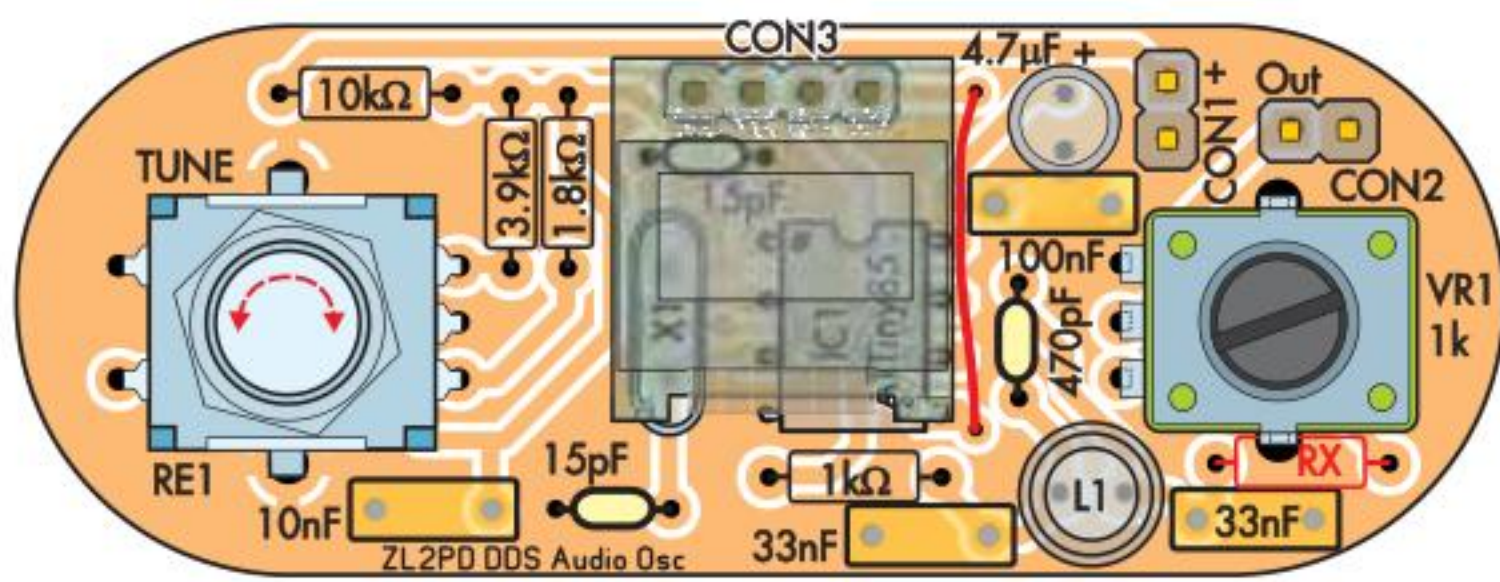


Fig.3: the components mounted on the PCB, with matching photos to assist assembly. Don't fit CON1 and CON2 when using the printed case. The wire link (shown in red) is not needed on commercially-made double-sided boards. The OLED screen (not shown in the photo at right) plugs into CON3 after the other components have been fitted.



Completing construction

The wiring to the slide power switch can now be completed. Begin by connecting the short red and black wires from the PCB to the switch. They should be about 50mm long. Make sure the power switch is off and the batteries are removed from the holder before soldering the power

no more than 3.3V!) and check that the Oscillator operates as expected.

Making the enclosure

The enclosure should now be prepared and assembled with the battery holder and power switch.

You can purchase a small Jiffy box enclosure from the usual suppliers if you wish. Alternately, you can download the 3D-printed custom enclosure parts files from the September 2021 page of the *PE* website and make them yourself if you have a 3D printer – see Fig.5.

There are two files required to print the enclosure; the first is for the front panel half of the enclosure, the second is for the rear half with its integrated battery holder. These are available for download in the standard STL format.

These can be 3D printed using standard PLA filament in any colour. The prototype enclosure was printed using grey filament with 50% fill and a 0.2mm-layer thickness, although these parameters are not critical. Each half requires about 2g of filament. If you do not have your own 3D printer, it is also possible to go to a 'maker hub' and do it there.

The two halves of the enclosure clip together firmly without the need for additional screws.

The rear section's integrated battery holder is dimensioned for two AAA cells. It requires the addition of battery contacts, wiring, and a battery joiner.

The battery contacts can be made by cutting 4mm and 3mm diameter circles from thin tinplate. A scrap piece of 0.2mm-thick tinplate was used for the prototype. It is possible to recycle a domestic tin can.

These handmade battery contacts should approximately match the divots

provided inside the battery holder at the switch end.

Solder a 10mm length of thin red multi-stranded insulated wire to the centre of the smaller circle and a similar length of black wire towards one edge of the larger circle. The wire should then be fed through the switch end of the battery holder, and the metal circles glued in place using epoxy.

Once the glue has set, test-fit a pair of AAA batteries. These should clip firmly into place side-by-side, but they will likely slide back and forth in the holder by about 1-1.5mm. Bend the battery joiner to take up that space. There is a slot provided for this folded joiner to be inserted into one end of the battery compartment.

To make this, cut a 60mm × 8mm strip of tinplate. Trim and bend it approximately into a flattened C shape to fit the available space. When folded correctly, the batteries will fit snugly into the battery holder. Along with the PLA plastic of the case, the arrangement will also provide a little tension to maintain good battery contact.

A useful accessory during this process is a voltmeter clipped to the black and red wire. This allows all of the connections to be checked for reliability during final assembly.

wiring in place.

The switch can now be mounted on the rear panel using a little hot melt glue or neutral-cure silicone sealant. If your slide switch has mounting tabs, trim these off first using a pair of side-cutters.

Mount the PCB in the front half of the enclosure, first feeding the output wires through the hole provided. The PCB assembly is mounted using the nuts and washers supplied with the rotary encoder and potentiometer. Vertical-mount potentiometers may not have nuts; in this case, it will just be the rotary encoder boss and nut holding in the board.

The small alligator clips may now be fitted to the output wires. Alternately, if you are using a Jiffy box, you may prefer to use a small output connector mounted on one end of the box. Options include a panel mounted RCA socket (eg, Jaycar Cat PS0270 or Altronics Cat P0161), or a 3.5mm audio socket (eg, Altronics Cat P0093 or Jaycar Cat PS0122).

Print the front panel artwork (Fig.4) and attach it to the front of the enclosure. The artwork can be printed using a colour laser or inkjet printer. Trim the artwork to size and cover it with self-adhesive transparent film. This panel

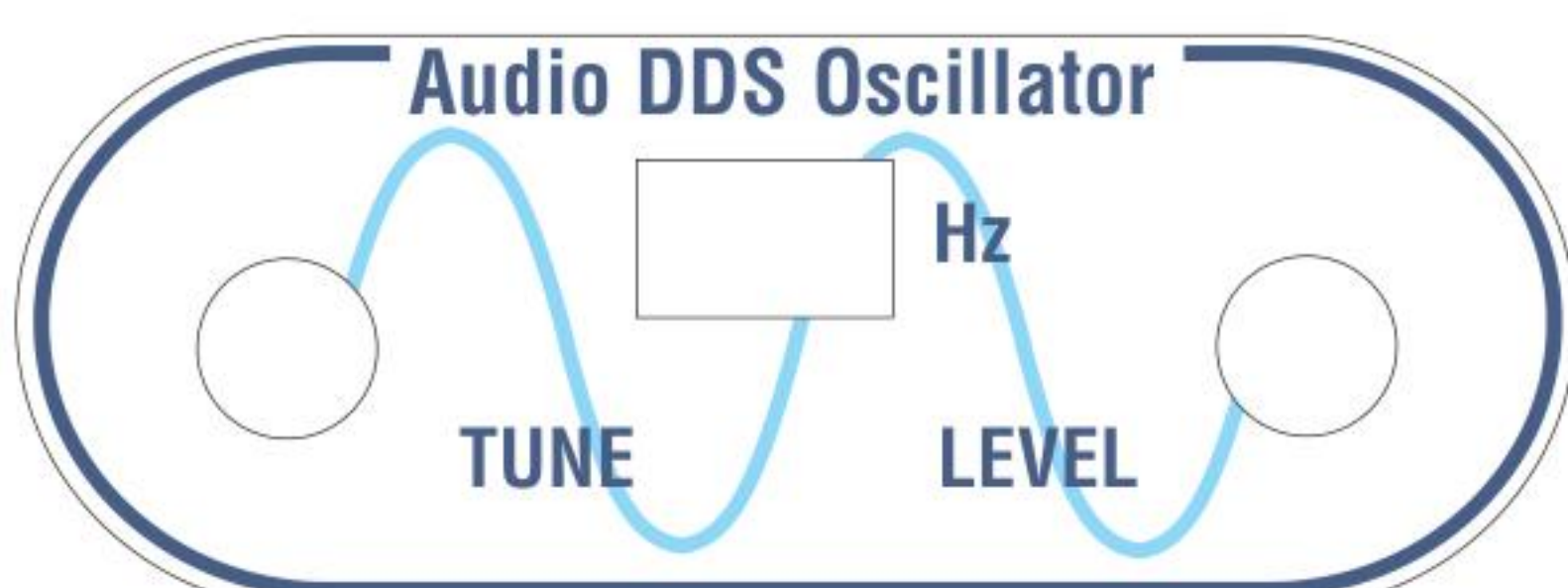


Fig.4: this artwork can be printed, laminated, cut out and attached to the front panel of the unit using glue or double-sided tape. You can also download this as a PDF from September 2021 page of the *PE* website

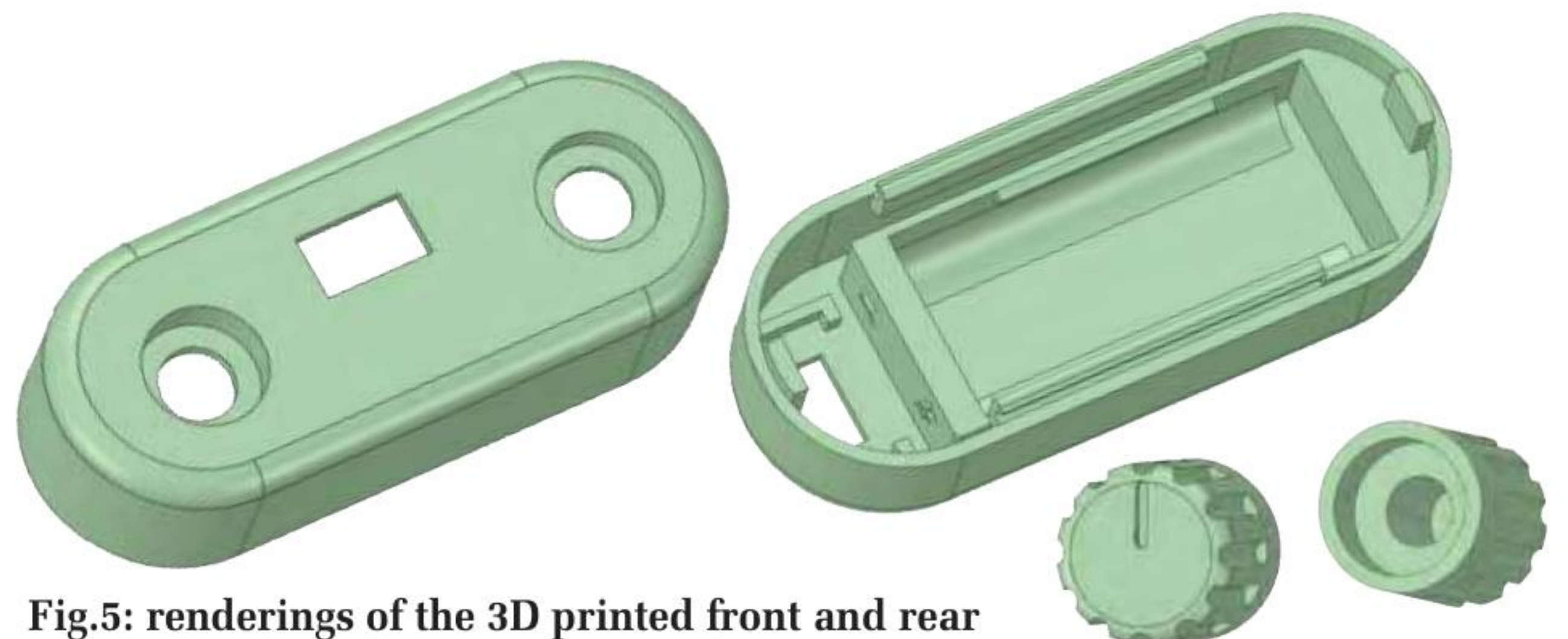


Fig.5: renderings of the 3D printed front and rear panels that form the custom case, along with the 3D-printed knobs. The associated STL files can be downloaded from our the September 2021 page of the *PE* website. The back panel has an integrated battery holder, but you need to fabricate or acquire the spring terminals and clips, as described in the text.

Programming the ATtiny85

If you haven't purchased a preprogrammed ATtiny85, you will need to program your blank chip before you can use it. You can use an AVR ISP programmer such as the USBasp (See www.fischl.de/usbasp/). It can be purchased online from many suppliers, often for a few pounds, including delivery.

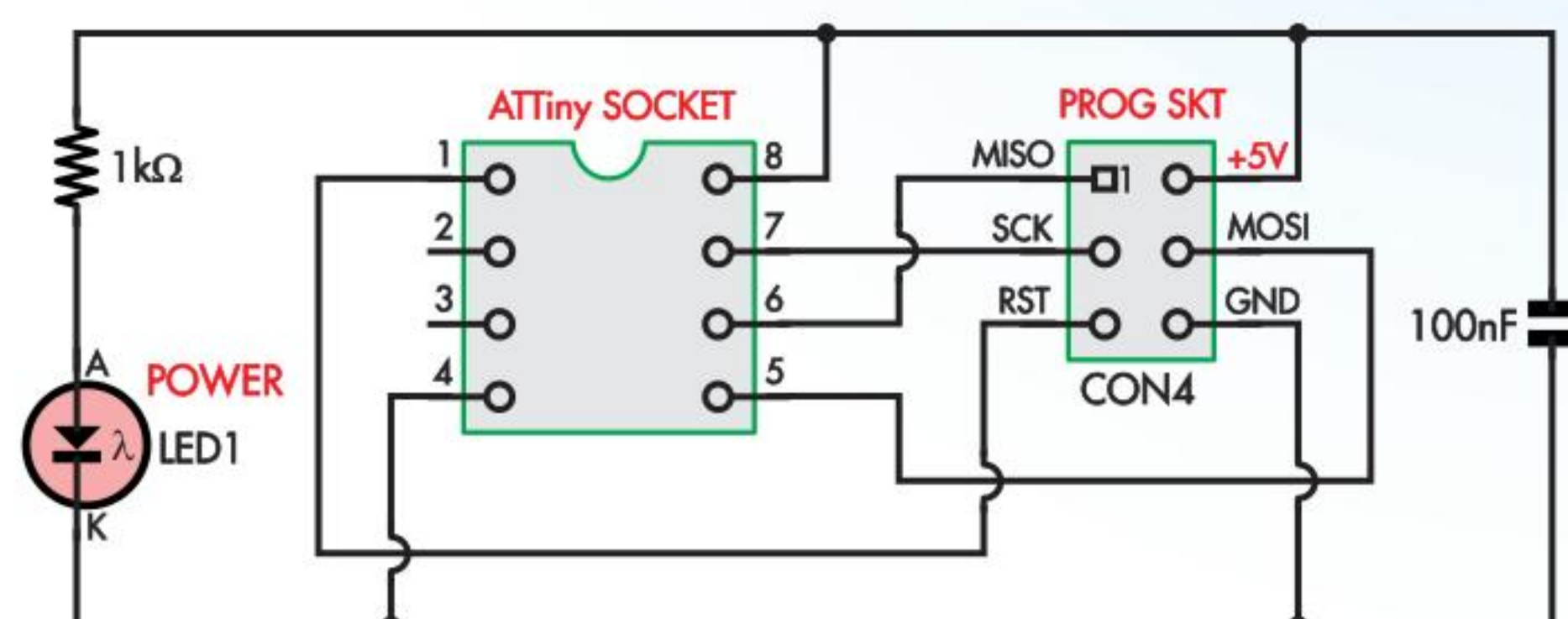
Such programmers are used with a PC or laptop; suitable software is available for Windows, Linux and macOS. This description will focus on the Windows platform.

The drivers for the chosen programmer must be installed before using it. The drivers for the USBasp can be obtained from the link above.

Programming software is also required. (Freeware) software for Windows includes eXtreme Burner (<https://bit.ly/pe-sep21-ext>), AVRDUDESS (<https://bit.ly/pe-sep21-avr>) and Khazama (<https://bit.ly/pe-sep21-khaz>).

There are many websites and YouTube videos describing the setup and use of these programs. Here is a summary of the procedure required to program the ATtiny85 for this project:

- 1) Load the USBasp drivers.
- 2) Plug in and complete the installation of the USBasp programmer. If the option is present on the USBasp programmer, and some boards support this feature, select 5V operation rather than 3.3V for programming the ATtiny85.
- 3) Download the programming software and install it.
- 4) Open the programming software and select ATtiny85 as the target device.
- 5) Download the HEX file for the audio DDS generator and select it as the file to be used to program the ATtiny85.
- 6) Plug the six-pin connector from the USBasp programmer into CON4 on the Programming Adaptor Board (more on this below).
- 7) Select 'Write FLASH buffer to chip' or 'Write – Flash' to program the ATtiny85 with the HEX file. The LEDs on the USBasp will blink furiously for about a minute while the HEX file is being



The ATtiny85 Programming Adaptor circuit just connects the micro pins to the 6-pin programming header, with a small power supply bypass capacitor.

- programmed. A bar graph may be displayed to show progress.
- 8) Program the ATtiny85's internal 'fuses'. These memory locations configure the operating characteristics of the ATtiny85 to suit the software being run on the device. To do this, type in the following settings into the relevant Fuse page/section of the programming software, then click on 'Write' to send the data to the fuses:

Low: 0xEF
High: 0x5F
Extended: 0xFF (unchanged)
Lock: 0xFF (unchanged)

- 8) Assuming the programmer reports the programming has been successful, remove the programming cable from the adapter board and transfer the ATtiny85 from the programming adapter board to its socket on the audio DDS oscillator PCB.

Programming Adaptor Board

There is no programming connector for the ATtiny85 on the oscillator PCB. I program my ATtiny85 chips using a separate adaptor built from a scrap of prototyping board with an 8-pin IC socket, the Atmel-standard 6-pin programming pin header and a couple of supporting components.

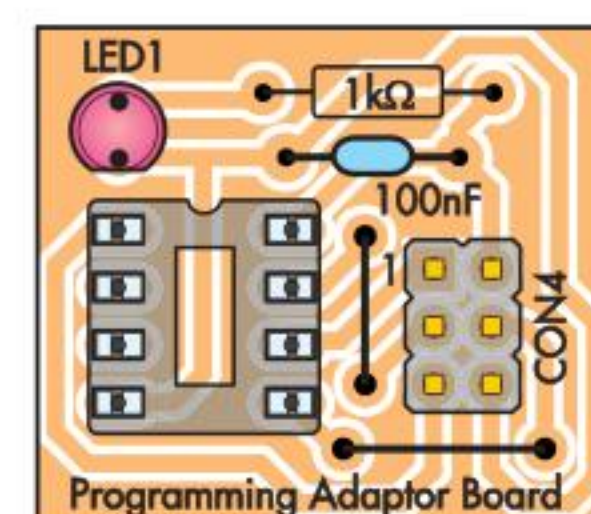
The circuit diagram for my adaptor and the equivalent PCB are shown below. For those wanting to make a little PCB for this programming adaptor, if you don't want to make it on veroboard, you can order this board when you order your main PCB (and possibly case), for just a couple of dollars more.

The resistor and LED are nice optional extras. They show when power is applied to the Programming Adaptor Board from the USBasp programmer.

The ATtiny85 to be programmed is plugged into the 8-pin IC socket; make sure it is oriented correctly, with its pin 1 dot near the notch. The USBasp programmer plugs into CON4, with its pin 1 towards the IC socket. Power for the programming adapter board comes from the USBasp.

If your USBasp or similar programmer has a selection of programming voltages available, it's best to select '5V' for reliable programming of the ATtiny85.

Fit the components as shown here; the two wire links can be made from component lead off-cuts. Pins 1 of both the IC and CON4 are at upper left.



artwork can then be glued to the front of the enclosure. Double-sided adhesive tape can be used quite successfully.

If using glue, then cover the rear of the artwork first with another piece of self-adhesive film to prevent the glue bleeding through the printed artwork.

The two knobs can now be fitted to the control shafts. The prototype used knobs specifically designed for the unit which were 3D-printed (see Fig.5). These STL files are also available for

Screen1: despite being quite tiny (at around 12mm diagonal – it's shown here about twice life size), the currently selected frequency is clear due to the bold font, with its four digits occupying the entire width of the screen.



downloading,. These slide firmly onto the respective control shafts. Alternately, see the parts list for commercially-made alternatives.

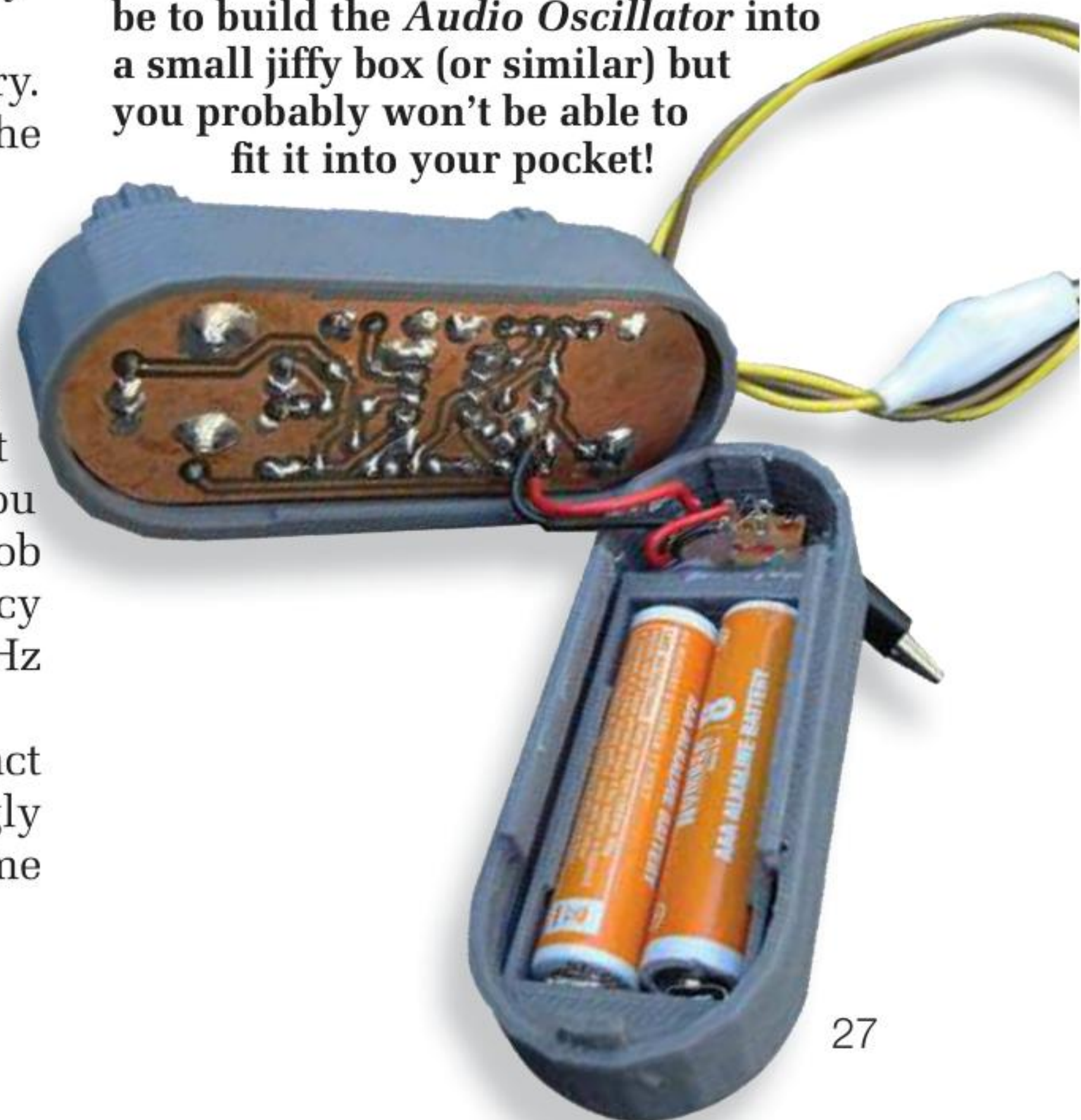
The final step is to install the battery. Then clip the case together, and the oscillator is ready for use.

Operation

It couldn't be easier. Switch it on, select the frequency you want with the tuning knob, set the desired output level with the level control, and you are in business. Press the tuning knob to step through the various frequency step options: 1Hz, 10Hz, 100Hz, 1kHz and then back to 1Hz again.

Despite its simplicity, this compact little audio oscillator is surprisingly useful. I hope one of these finds a home in your shirt pocket too.

One half of the custom case houses the PCB while the batteries fit neatly into the other half. The alternative would be to build the Audio Oscillator into a small jiffy box (or similar) but you probably won't be able to fit it into your pocket!



High-power ULTRASONIC Cleaner

Part 1
By John Clarke



This large, *High-power Ultrasonic Cleaner* is ideal for cleaning bulky items such as mechanical parts and delicate fabrics. It's also quite easy to build and is packed with features.

You've probably seen the small, low-cost ultrasonic cleaners available online. They're great for cleaning items like jewellery or glasses, but what if you want something a bit bigger and more powerful to suit a wider variety of cleaning jobs?

Cleaning fuel injectors, an old carburettor or any other intricate part is a messy and time-consuming task, requiring soaking in harsh solvents such as petrol, kerosene or a degreaser and then scrubbing with various brushes to clean up the parts. It is a difficult and tedious task, and often does not reach the small apertures that are usually the essential areas that need cleaning.

Our *Ultrasonic Cleaner* makes this task so much easier. Just place the components in a solvent bath, press a button and then come back later to remove the parts in sparkling clean condition. It will even clean internal areas! It uses a high-power piezoelectric transducer and an ultrasonic driver to release the dirt and grime with ultrasonic energy.

For more delicate parts, the power can be reduced to prevent damage to the items being cleaned.

How does it work?

A metal container is filled with a solvent, deionised water, or normal hot water and a detergent or wetting agent.

The ultrasonic transducer agitates the contents of the bath; at higher power levels, the ultrasonic wavefront causes cavitation, creating bubbles which then collapse. This is shown in Fig.1.

As the wavefront passes, normal pressure is restored, and the bubble collapses to produce a shockwave. This shockwave helps to loosen particles from the item being cleaned (Fig.2). The size of the bubbles is dependent upon the ultrasonic frequency – the higher the frequency the smaller the bubble.

We are using the commonly available bolt-clamped Langevin ultrasonic transducer, depicted in Fig.3.

Features

- Drives a nominal 40kHz, 50W or 60W-rated transducer
- Adjustable power level
- Power level display
- Stop and Start buttons with run operation indication
- Auto-off timer from 20 seconds to 90 minutes
- Soft start
- Over-current and startup error shutdown and indication
- Power level diagnostics
- Automatic or manual transducer calibration
- Standing wave minimisation
- Supports a resonance frequency of 34.88kHz to 45.45kHz



The 'works' of our Ultrasonic Cleaner before the transducer is attached to the cleaning bath. Operation is pretty simple: turn on, set the timer and push the 'start' button!

It comprises piezoelectric discs sandwiched between metal electrodes. The centre bolt not only holds the assembly together, but is critical in ensuring the piezo elements are not damaged when being driven. The bolt is torqued to a pre-determined tension and locked (glued) in place to prevent it loosening.

The bolt tension ensures the piezo discs always remain in compression, even while it is operating, preventing the discs from breaking apart.

When a voltage is applied to the piezoelectric discs, forces are generated by the piezo elements that move the two metal ends closer together and then further apart at the ultrasonic drive rate. Our *Ultrasonic Cleaner* drives the piezo transducer at close to its nominal 40kHz resonant frequency.

Fig.4 shows the power applied versus frequency for the particular ultrasonic transducer we are using. It claims to have a resonant frequency of 40kHz with a 1kHz tolerance either side of this frequency. We found that the transducer resonates at 38.8kHz under load.

The transducer drive frequency needs to be controlled to within a fine tolerance to maintain a consistent power level. A small change in frequency from the resonant point will reduce the power quite markedly. Additionally, their impedance varies depending on load. So when operating in free air, the impedance is much lower compared to when the transducer is driving a bath full of cleaning fluid.

Circuit details

The circuit of the *Ultrasonic Cleaner* is shown in Fig.5. It is based around a PIC16F1459 microcontroller (IC1). This controls the two MOSFETs (Q1 and Q2) that drive the primary windings of transformer T1 in an alternating

fashion. T1 produces a stepped-up voltage of 100V AC (RMS) to drive the ultrasonic transducer.

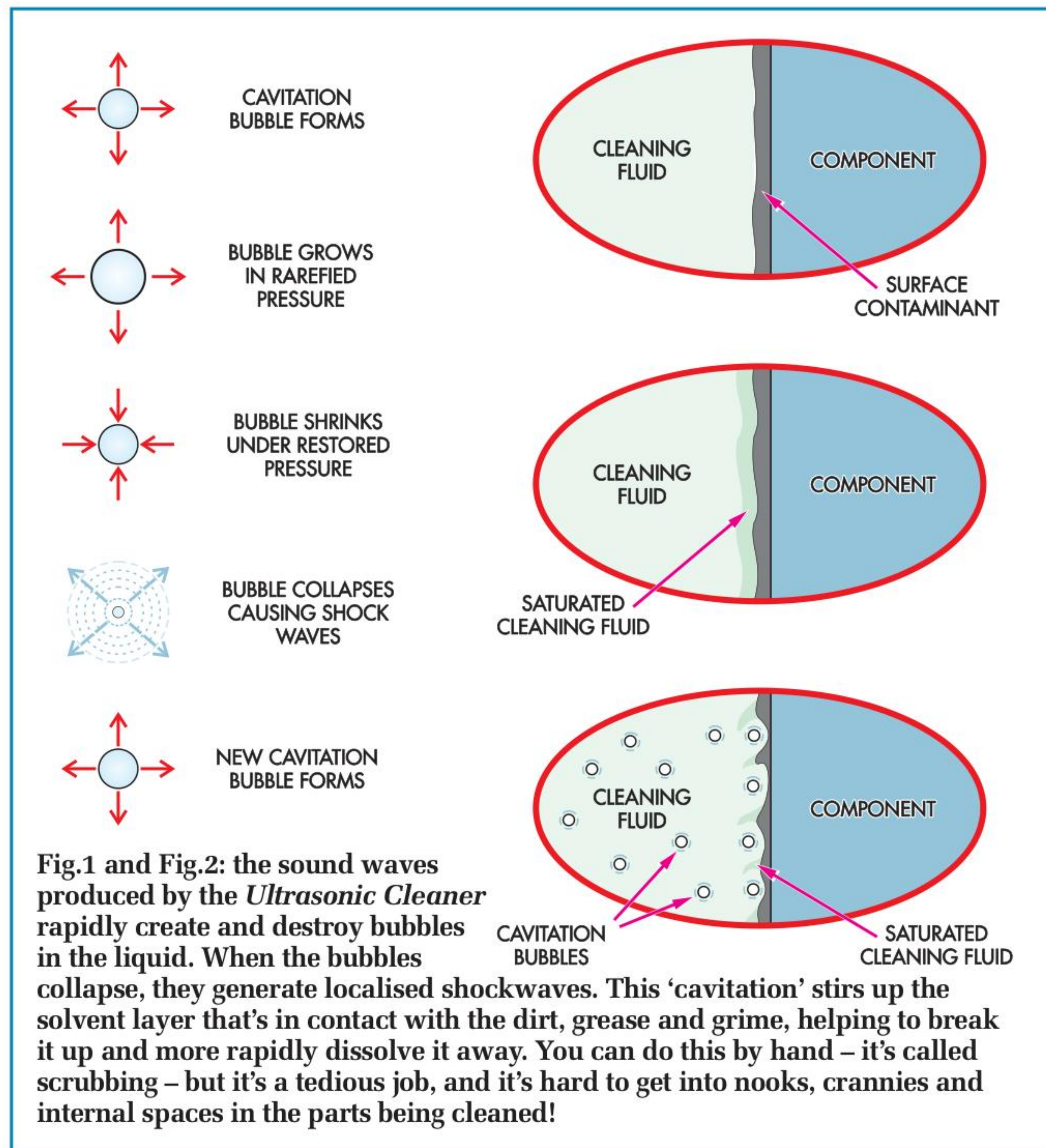
IC1 also drives the power LED (LED1) and level LEDs (LED2-LED6); plus it monitors the timer potentiometer (VR1) and switches S2 and S3, used for starting and manually stopping the cleaner operation.

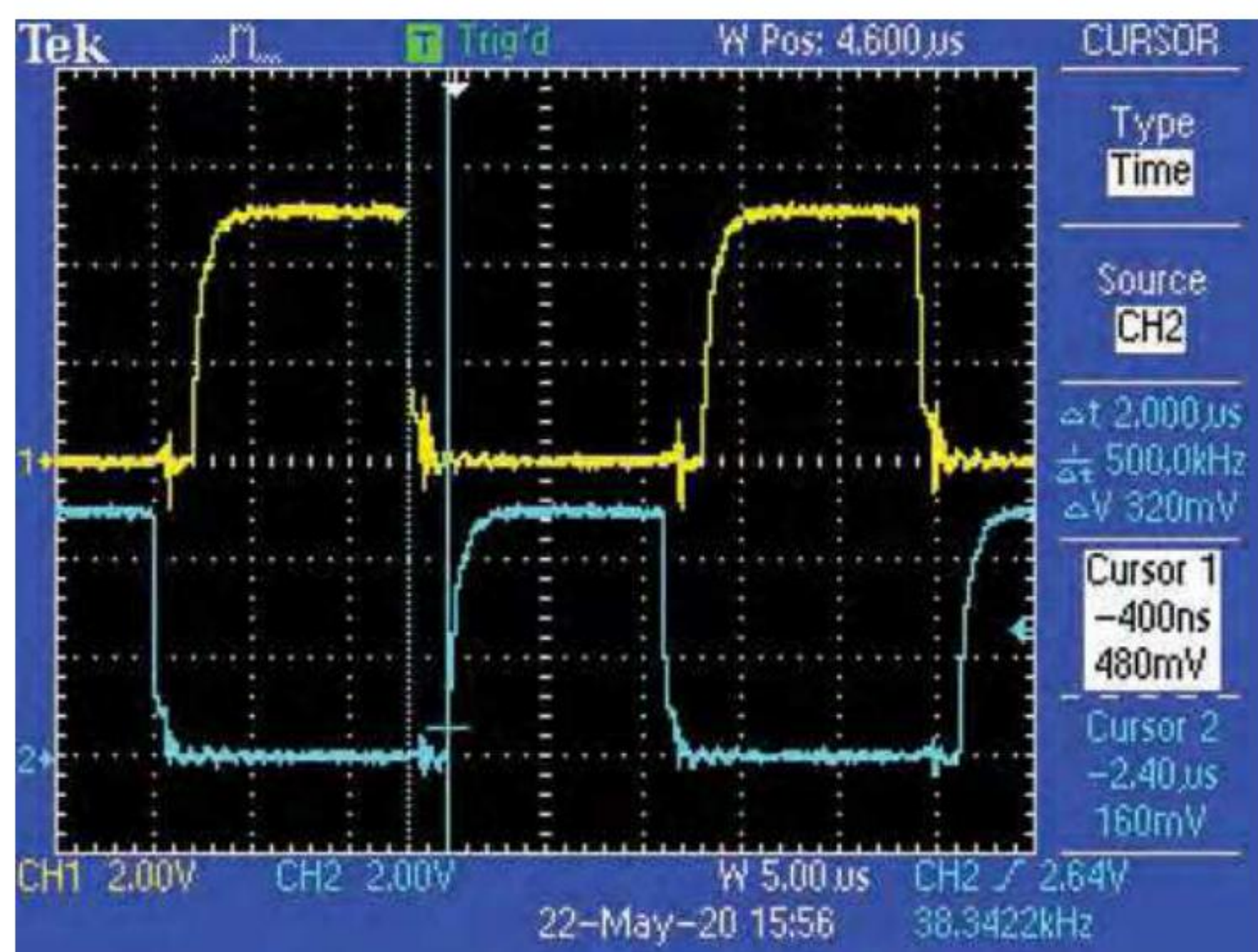
IC1 also monitors the current flowing through MOSFETs Q1 and Q2 at its AN11 analogue input, at pin 12. And it controls the soft-start charging

of the main bypass capacitor using transistor Q5 and MOSFET Q6.

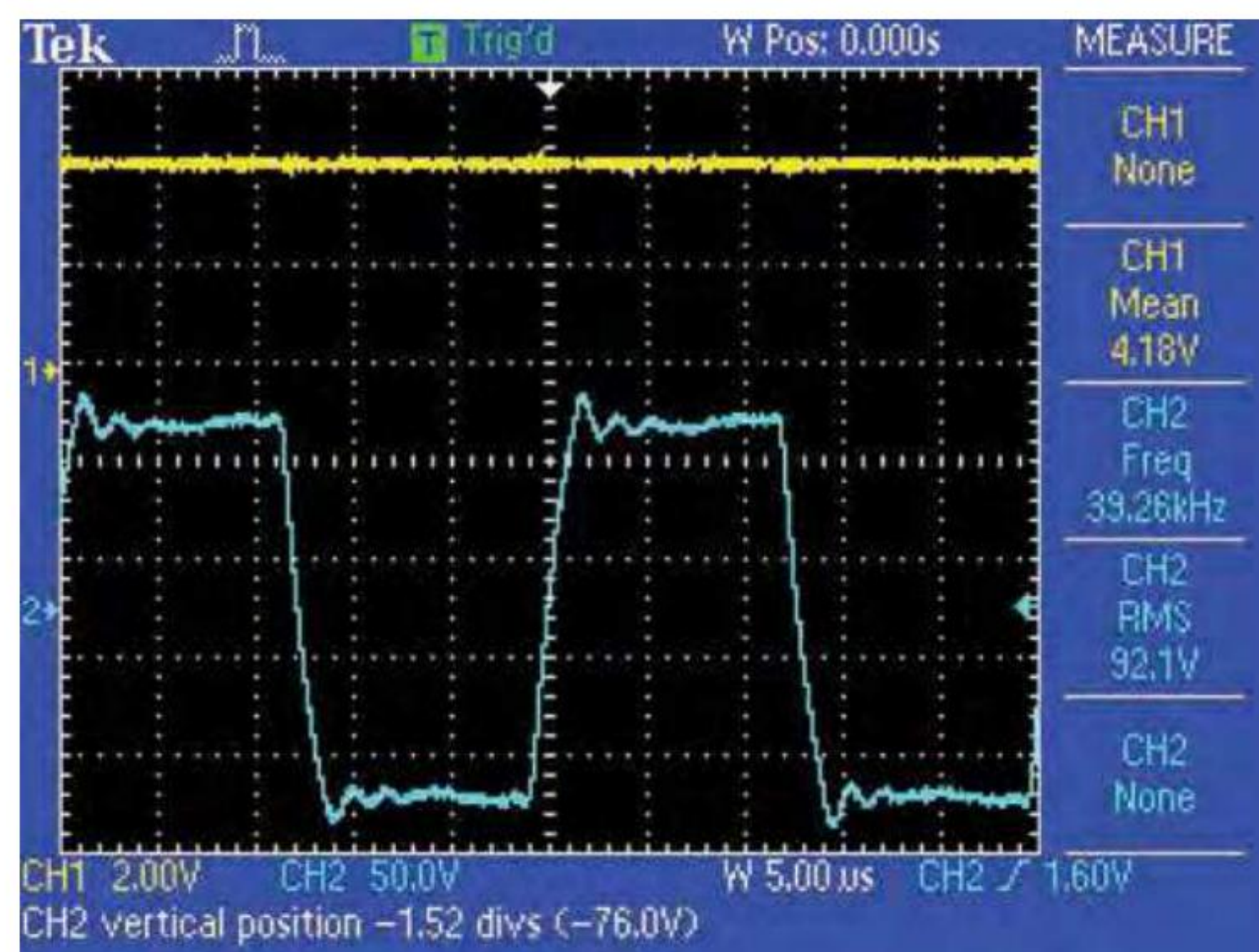
Transformer drive

A complementary waveform generator within IC1 is used to drive MOSFETs Q1 and Q2 in push-pull mode. The transformer is centre-tapped to allow this type of drive. IC1's PWM generator includes an adjustable dead time, so that there is time for one MOSFET to switch off before the other MOSFET is switched on (Scope1). This prevents 'shoot-through', which would otherwise cause the MOSFETs to overheat.





Scope1: the gate drive to Q1 (top trace, yellow) and Q2 (bottom trace, cyan) measured at pins 5 and 6 of IC1. The vertical cursors show the dead time when both MOSFETs are not driven as 2µs. That is for when Q1 switches off and Q2 switches on; the dead time is the same between Q2 switching off and Q1 switching on.



Scope2: the lower trace (cyan) shows the transformer output voltage when driving the ultrasonic transducer at 39.26kHz. The top trace shows the current measurement voltage at the AN11 input of IC1 (TP1). 4.18V represents a 2.98A current driving the transformer primary with a 12V supply. This equates to approximately 35.8W delivered to the transducer.

IC1's RC5 and RC4 digital outputs provide the complementary gate drive signals for MOSFETs Q1 and Q2. Since these outputs only swing from 0V to 5V, we are using logic-level MOSFETs. Standard MOSFETs require gate signals of at least 10V for full conduction, but logic-level MOSFETs will typically conduct fully at 4.5V, or sometimes even lower voltages.

With the STP60NF06L MOSFETs we are using, the on-resistance (between drain and source) is 14mΩ at 30A with a 5V gate voltage. They are rated at 60A continuous and include over-voltage transient protection that clamps the drain-to-source voltage at 60V.

Q1 and Q2 are driven alternately and these, in turn, drive the separate halves of the transformer primary of T1, which has its centre tap connected to the +12V supply. When MOSFET Q1 is switched on, current flows in its section of the transformer primary

winding. Q1 remains on for less than 25µs (assuming a 40kHz operating frequency) and is then switched off.

Both MOSFETs are off for two microseconds before Q2 is switched on. Q2 then draws current through its section of the T1 primary winding and remains on for the same duration as for Q1. Both MOSFETs remain off again for two microseconds before Q1 is switched on again. The gap when both MOSFETs are off is the 'dead time' and accounts for the fact that the MOSFET switch-off takes some time.

Without dead time, the two MOSFETs would both be switched on together for a short duration. This would cause massive short-circuit current spikes, not only resulting in overheating of the MOSFETs but also drawing large current spikes from the supply filter capacitor and DC power supply.

The alternate switching action of the MOSFETs generates an AC

square wave in the secondary winding of transformer T1. With a turns ratio of 8.14:1 (57-turn secondary and 7-turn primary), and 12V AC at the primary, the secondary winding delivers about 98V AC to the piezo-electric transducer.

Standing waves

Running the *Ultrasonic Cleaner* at a constant frequency near resonance is efficient, since the impedance of the transducer is almost purely resistive under those conditions. However, this is not ideal for minimising standing waves within the cleaning bath. Standing waves can build up in strength while the frequency remains constant.

These waves are caused by reflections from the parts being cleaned and the tank walls being in-phase. This can damage delicate parts.

Our *Ultrasonic Cleaner* has the option of reducing the power for use with

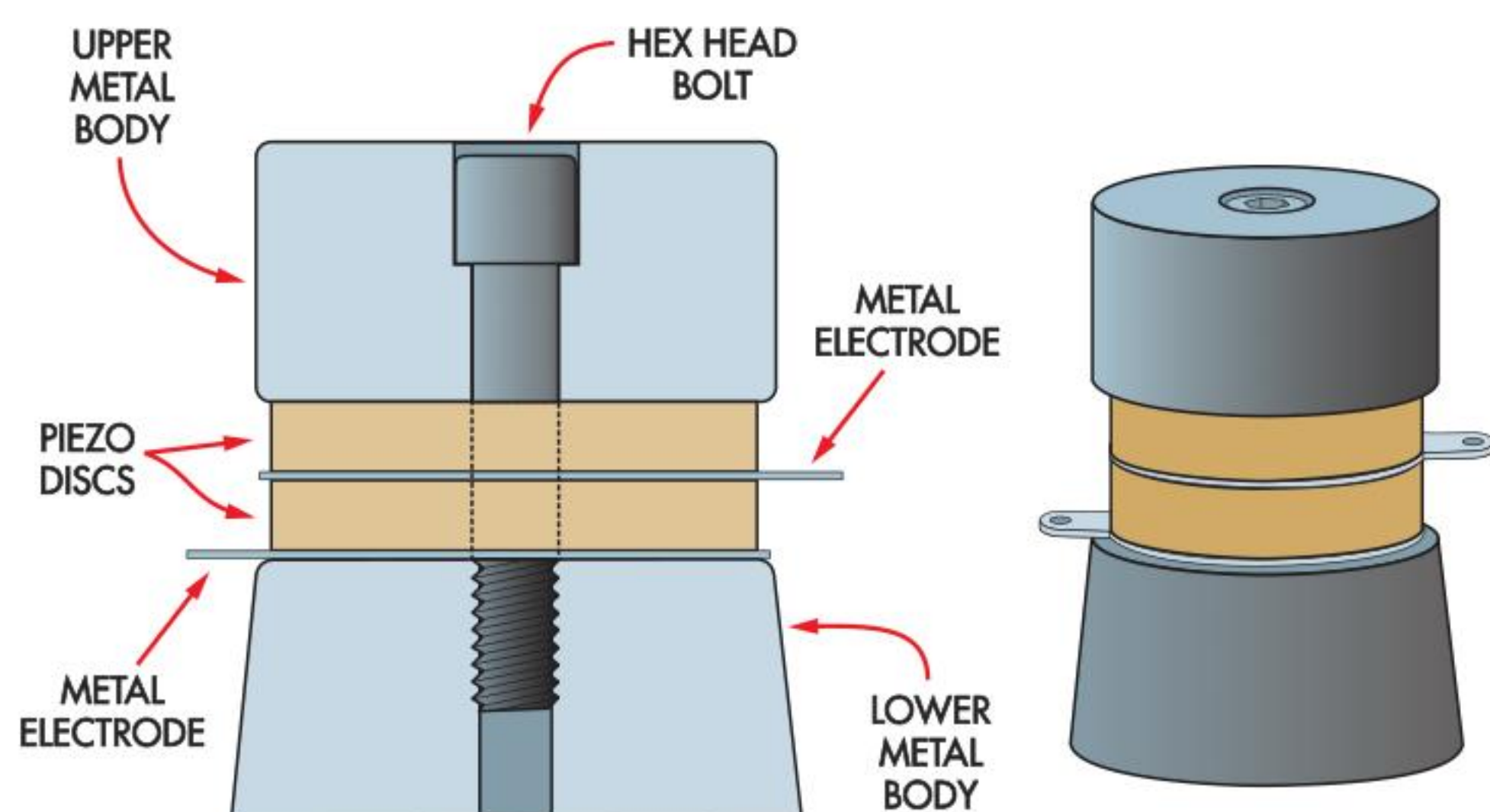


Fig.3: this shows the construction of the ultrasonic transducer that we're using. Two piezoelectric (ceramic) discs are sandwiched between the two halves of the body, with electrodes to allow a voltage to be applied across the piezo elements. The compression of the piezoceramics due to the tension from the bolt holding the whole thing together is critical to preventing early failure from the ultrasonic vibrations.

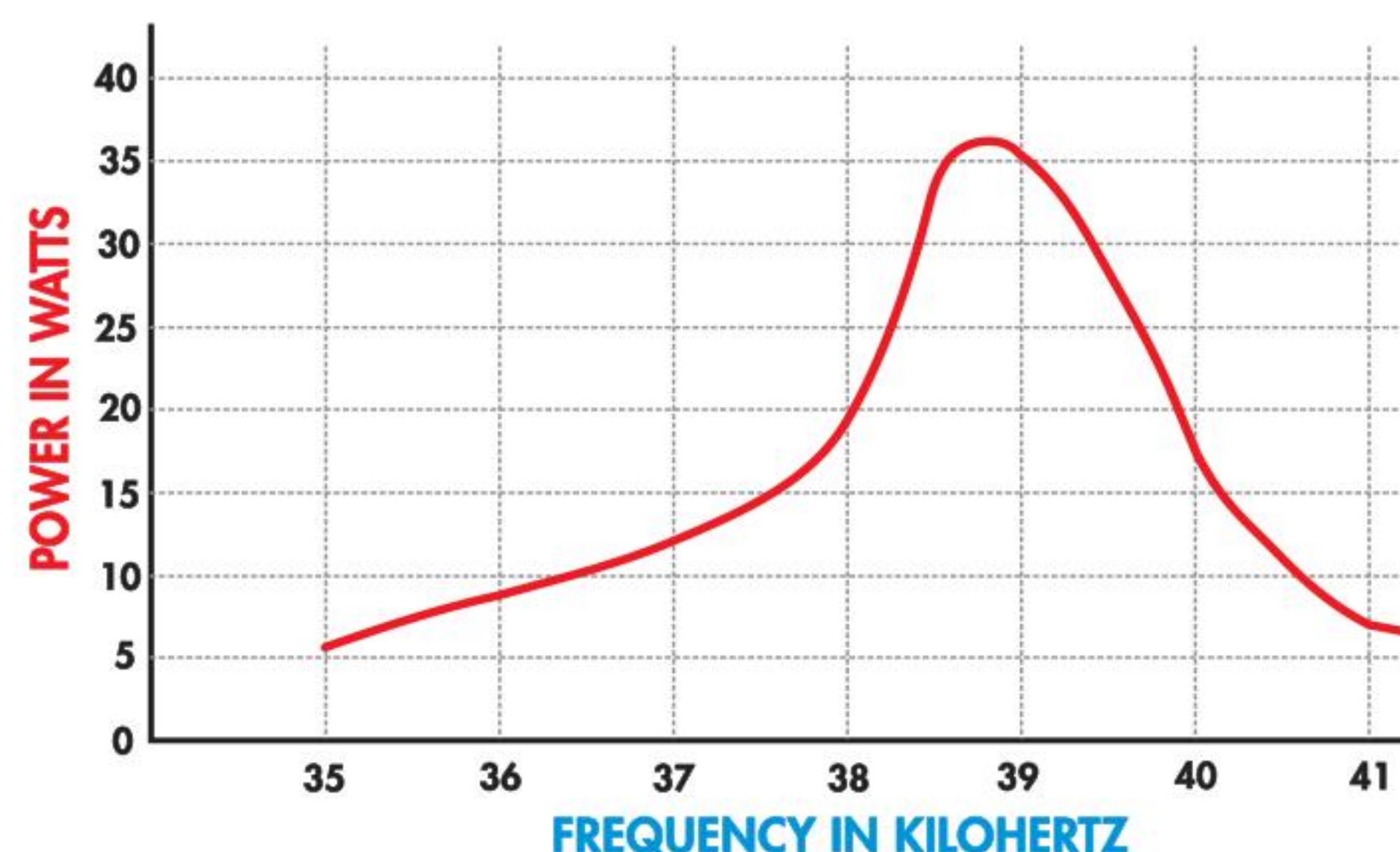
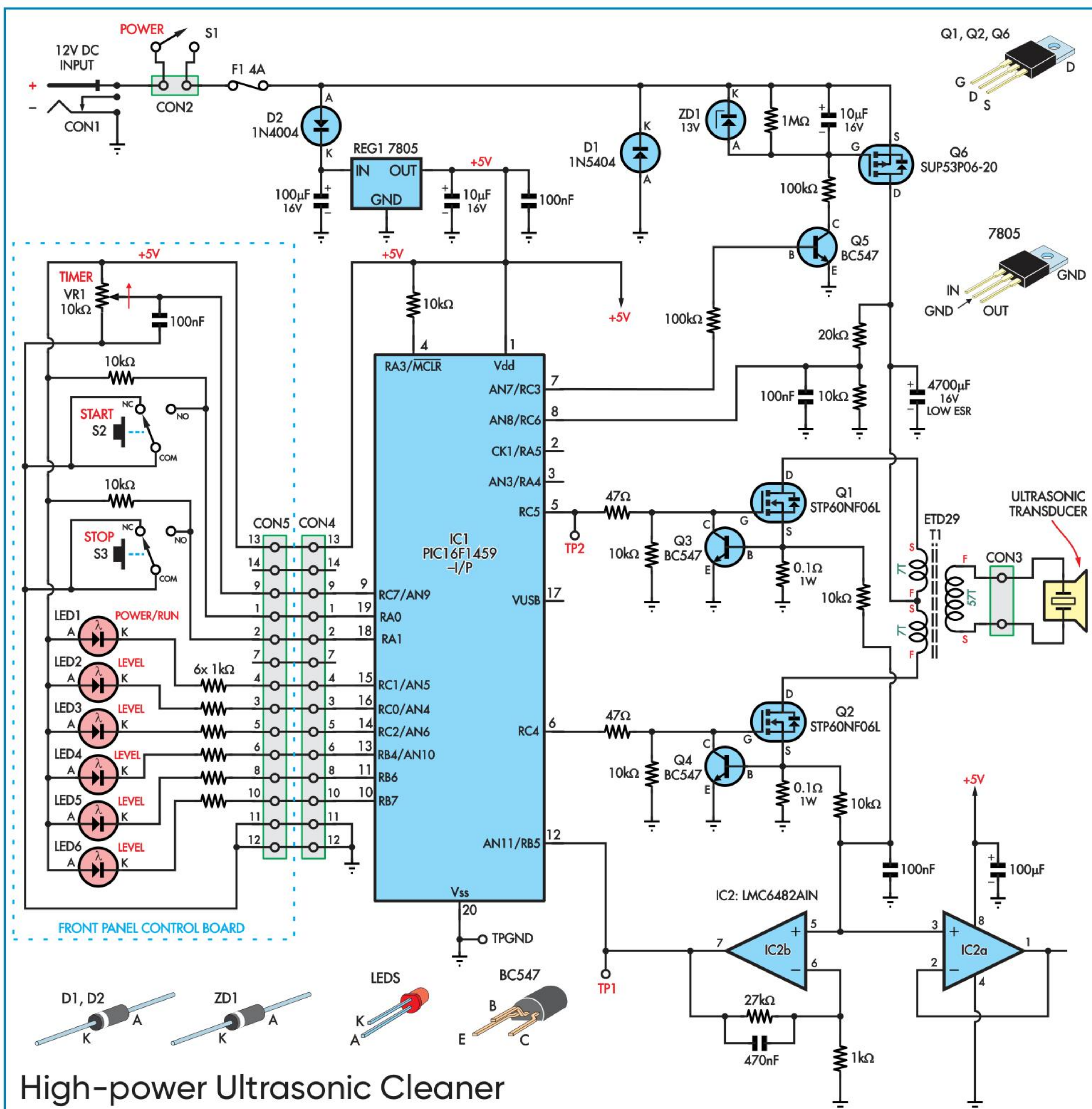


Fig.4: the frequency vs power curve for the transducer in our prototype. Most transducers with a nominal 40kHz resonance should be similar, but the exact frequency of the peak will vary, as will the steepness of the slopes. Hence, our *Ultrasonic Cleaner* has an automatic calibration procedure to find this peak; the 100% power setting runs it at a frequency close to the peak, while lower power settings are at higher frequencies.



High-power Ultrasonic Cleaner

Fig.5: the complete *Ultrasonic Cleaner* circuit. IC1 produces complementary drive signals to the gates of MOSFETs Q1 and Q2, which in turn drive the primary of transformer T1 in a push-pull manner. This results in around 100V AC at CON3. Current is monitored via two 0.1Ω shunt resistors at the sources of Q1 and Q2, via amplifier IC2b into analogue input AN11 of IC1; the power is computed from this and a voltage measurement at analogue input AN8.

delicate parts, but even larger parts can have delicate sections within them, especially in thin-walled cavities.

To avoid standing waves, the frequency can change over time to prevent the constant phase of the waveform, which would cause constructive interference at various locations in the bath. As the power versus frequency graph shows, changing the frequency even by a small amount will drastically alter the power. So it is not ideal if the frequency is varied continuously, as it reduces the cleaning power.

Instead, we operate the transducer at a fixed frequency for 10 seconds at

a time, then run it over a range of different frequencies for a short time before returning to the maximum power frequency for another 10-second burst.

In the intervening time, the frequency varies in small 37.5Hz steps over a 2.4kHz range for around 400ms. That means that power is reduced only about 4% of the time. The cycling in frequency alters the phase of the ultrasonic vibrations in the bath, giving time for standing waves that occur during the fixed frequency period to die down, thus preventing them from building up to a damaging level.

Over-current protection

The over-current protection for the MOSFETs is provided in two ways. Both of the methods rely on current detection via the voltage across the 0.1Ω between the sources of Q1 and Q2 and ground.

The first method uses NPN transistors Q3 and Q4. These have their base-emitter junctions connected across those 0.1Ω current-sense resistors.

Over-current starts when the voltage across the 0.1Ω resistor exceeds about 0.5V; ie, with more than 5A through either Q1 or Q2. The associated transistor Q3 or Q4 then begins to conduct.

The current flowing from its collector to its emitter reduces the gate voltage to the associated MOSFET. This has the effect of increasing the MOSFET on-resistance, which then reduces the current. This protection is a fast-acting, cycle-by-cycle protection measure.

At the same time, the voltages across the two 0.1Ω current-sense resistors are averaged by a pair of $10k\Omega$ resistors and filtered by a $100nF$ capacitor. This averaged voltage is then applied to non-inverting input pin 5 of op amp IC2, which amplifies the signal 28 times $((27k\Omega \div 1k\Omega) + 1)$. The averaging effectively halves the sensed voltage, since only one of Q1 or Q2 is on at any given time.

So this results in an overall amplification of 14. The output from pin 7 of IC2b is measured by the AN11 analogue input of IC1 (pin 12) – see Scope2.

This voltage is converted to a digital value and processed by IC1. Should this voltage stay at 4.9V or more over a 160ms period, the drive to the transducer is switched off.

This voltage represents an average of 350mV measured across each 0.1Ω resistor, or a 3.5A average current flow. That's calculated as $(4.9V \div 14) \div 0.1\Omega$.

An over-current error is indicated by flashing LED2, LED4 and LED6 on the front-panel level display. When this happens, the power will need to be switched off and restarted to resume cleaning. If the problem persists, the cause will need to be found.

Power control

The current measured at the AN11 input is also used for controlling the power applied to the ultrasonic transducer. The maximum power rating of the transducer is 50W, but this is not a continuous rating. The recommended continuous power is 43W. We limit power to a more conservative 36W. For a 12V supply, the current required for this level of power is 3A.

During operation, the current is monitored via AN11 and the drive voltage is also sampled, via a resistive divider, at analogue input AN8 (pin 8). This allows the micro to calculate the power flowing into the transformer as the frequency is adjusted, so that it can maintain the power at the required level.

IC1's instruction clock is derived from its internal oscillator, and thus the PWM output frequencies are derived from this as well. The internal oscillator can be adjusted in small steps using the OSCTUNE register. This can vary the internal oscillator frequency over a 12% range in 128 steps. For the 40kHz drive to the ultrasonic transducer, this allows a 4.8kHz control range in steps of 37.5Hz.



The 40kHz transducer is available online. Remember that if you do buy online you need to make sure you get a 40kHz type – there are other frequencies available and they look pretty much identical. (See the NOTES in the Parts list opposite).

The 37.5Hz-step resolution is sufficiently small to drive the ultrasonic transducer at the desired power level. However, the OSCTUNE register does not have sufficient frequency range to ensure we can drive an ultrasonic transducer that is resonant outside the range of 37.6kHz to 42.4kHz.

To widen the operating range, the unit calibrates itself automatically (it can also be initiated manually). This finds the approximate resonant frequency of the transducer using a coarser adjustment. Fine-tuning is then done via OSCTUNE; this allows a variety of different transducers to be used.

This coarser calibration is performed using the PR2 register, which sets the period and thus the frequency of the PWM drive waveform. For our circuit, this provides steps of approximately 540Hz. We restrict the coarse adjustment range to be from 34.88kHz to 45.45kHz. This range caters for all transducers that have a nominal 40kHz resonance.

So the transducer's resonance is found to within 540Hz by adjusting PR2, and this value is stored in non-volatile Flash memory. OSCTUNE can then vary the frequency at least 1.8kHz above and 1.8kHz below the value initially set by the PR2 register ($1.8kHz \approx 2.4kHz - 540Hz$).

Different power levels are available by adjusting the drive frequency. The highest power is at the frequency closest to resonance, while lower power

levels use a frequency above resonance that has the transducer producing a lower power.

Nine power levels are available, ranging from 100% (36W) down to 10% (about 3.6W). Depending on the transducer characteristics, the lowest power level may not be available.

LED indicators

LEDs 2-6 indicate which of the nine power levels is selected, with LED2 lit to indicate the lowest power level. The next step up is with LED2 and LED3 lit, then LED3 and so on until LED6 only is on, showing the highest power level.

The power level is adjusted by holding down the Start switch. It will then cycle up through the nine possible levels to the maximum, then down again. The switch can then be released at the desired level setting. The transducer is not driven during power level adjustments.

The On/Run LED (LED1) shows when power is applied to the circuit. This LED also acts as an operation indicator. The LED goes out during transducer calibration and then lights when the required value for PR2 is found.

This takes a few seconds, unless there is something wrong, such as when there is no transducer connected.

Once running, LED1 only lights when the transducer is being driven at the required power setting; it acts as an 'in lock' indicator.

When the Stop switch is pressed, the drive to the transducer ceases, the level LEDs go off and the power LED turns on. LED1 then goes out when the main power source is switched off via S1, or if the supply itself is disconnected or switched off.

Cleaning timer

VR1 is the timer control. The voltage from its wiper is applied to the AN9 analogue input of IC1 (pin 9), and it varies between 0V and 5V. This corresponds to a timer range from 20 seconds through to 90 minutes.

The timer starts when the Start switch is pressed. After the selected period, the transducer drive stops.

Switches S2 and S3 connect to the RA0 and RA1 inputs of IC1 respectively. The inputs are held high (at 5V) by $10k\Omega$ pull-up resistors. A closed switch is detected when it is pressed as the input is pulled to 0V.

Note that we are using pushbutton changeover switches that have common (C), normally closed (NC) and normally open (NO) contacts.

The pins on the switch are in a line, with the common pin at one end, NO in the middle and NC at the other end. Usually, that means that you would

Parts list – High-power Ultrasonic Cleaner

- 1 double-sided PCB coded 04105201, 103.5 x 79mm
- 1 double-sided PCB coded 04105202, 65 x 47mm
Both PCBs available from the PE PCB Service
- 1 panel label, 115 x 90mm (see text)
- 1 diecast aluminium box, 115 x 90 x 55mm (Jaycar HB5042)
- 1 50/60W 40kHz ultrasonic horn transducer (resonance impedance 10-20Ω) [see **NOTES** below]
- 1 12V DC 60W switchmode supply or similar
[Jaycar GH1379, Altronics MB8939B] **OR**
- 1 12V battery (10Ah or greater) with 5A+ rated twin lead
- 1 EPCOS ETD29 13-pin transformer coil former, B66359W1013T001 (T1)
[RS Components 125-3669, element14 1422746]
- 2 EPCOS ETD29 N97 ferrite cores, B66358G0000X197 (T1)
[RS components 125-3664, element14 1422745]
- 2 EPCOS ETD29 clips, B66359S2000X000 or equivalent (T1)
[RS components 125-3668, element14 178507]
- 1 6A SPST mini rocker switch (S1)
[Altronics S3210, Jaycar SK0984]
- 2 SPDT momentary push button switches (S2,S3)
[Altronics S1393]
- 2 switch caps for S2 and S3 [Altronics S1403]
- 1 5A PCB-mount barrel socket, 2.5mm ID (CON1)
[Jaycar PS0520, Altronics P0621A]
- 1 5A barrel plug, 5.5mm OD x 2.5mm ID
[Jaycar PP0511, Altronics P0165] (optional)
- 1 vertical 2-pin pluggable header socket with screw terminals (CON2) [Jaycar HM3112+HM3122]
- 1 2-way PCB mount screw terminal with 5.08 spacing (CON3)
[Jaycar HM3130, Altronics P2040A]
- 1 14 pin box header (CON4) [Altronics P5014]
- 1 14 pin IDC plug (for CON4) [Altronics P5314]
- 1 14-pin IDC transition plug (CON5) [Altronics P5162A]
- 2 3AG PCB-mounting fuse clips (F1)
- 1 4A 3AG fuse (F1)
- 1 10kΩ 16mm linear potentiometer (VR1)
- 1 knob to suit potentiometer
- 1 20-pin DIL IC socket (for IC1)
- 1 8-pin DIL IC socket (for IC2)
- 3 TO-220 silicone washers and bushes
- 4 stick-on rubber feet

Transducer housing parts

- 1 50mm length PVC DWV (Drain, Waste and Vent) fittings; end cap and adaptor **or** 1 40mm length of 50mm ID pipe
- 1 cable gland for 3-6.5mm cable
- Neutral cure silicone sealant (eg, roof and gutter)
- Epoxy resin (eg, JB Weld)

Parts for testing

- 1 100mm length of 0.7mm tinned copper wire
- 4 9mm-long M3 tapped spacers
- 4 M3 x 6mm machine screws
- extra length of 0.63mm diameter enamelled copper wire

Cables, wiring and hardware

- 1 M3 x 6mm machine screw (for REG1)
- 3 M3 x 9mm machine screws (for Q1, Q2 and Q6)
- 4 M3 hex nuts
- 1 cable gland for 3-6.5mm diameter cable
- 1 800mm length of 1mm diameter enamelled copper wire (T1 primary)
- 1 3.6m length of 0.63mm diameter enamelled copper wire (T1 secondary)
- 1 1m length of 0.75mm square area dual sheathed cable or figure-eight wire (for transducer connection)
- 1 160mm length of 5A (1mm²) hookup wire
- 1 200mm length of 14-way ribbon cable
- 8 PC stakes
- 1 30mm length of 5mm heatshrink tubing (for S1 connections)
- 1 roll of electrical insulating tape

Semiconductors

- 1 PIC16F1459-I/P microcontroller programmed with 0410520A.hex (IC1)
- 1 LMC6482AIN CMOS dual op amp (IC2)
- 1 7805 5V 1A linear regulator (REG1)
- 2 STP60NF06L logic level N-Channel MOSFETs (Q1,Q2)
- 3 BC547 NPN transistors (Q3-Q5)
- 1 SUP53P06-20 P-channel MOSFET (Q6)
- 1 13V 1W zener diode (ZD1)
- 1 1N5404 3A diode (D1)
- 1 1N4004 1A diode (D2)
- 6 3mm LEDs (red or green) (LED1-LED6)

Capacitors

- 1 4700μF 16V low-ESR PC electrolytic
- 2 100μF 16V PC electrolytic
- 2 10μF 16V PC electrolytic
- 1 470nF MKT polyester
- 4 100nF MKT polyester

Resistors (0.25W, 1% unless specified)

- 1 1MΩ 2 100kΩ 1 27kΩ 1 20kΩ
- 8 10kΩ 7 1kΩ 2 47Ω
- 2 0.1Ω 1W (SMD 6432/2512-size; Panasonic ERJL1WKF10CU or similar) [RS Components 566-989]

NOTES: The transducer is rated at 50W and designed for 40kHz operation. At the time of publication, **eBay.co.uk** part number 283977349993 is suitable (ensure you choose the 50W/40kHz option). Otherwise, a search on line for '50/60W 40kHz ultrasonic horn transducer, resonance impedance 10-20Ω' will yield further options.

You can get the remaining electronic parts for this project from the usual suspects (for purchasers outside Aus/NZ, the Jaycar/Altronics references provide sufficient information for choosing parts); use element14, Digi-Key or RS Components for the more specialised parts.

The PVC components for the transducer housing are readily available from hardware and DIY stores.

need to orient the switch correctly on the PCB for correct operation.

However, we have designed the PCB pattern so that either orientation will work by wiring the C and NC connections together on the PCB.

Power supply

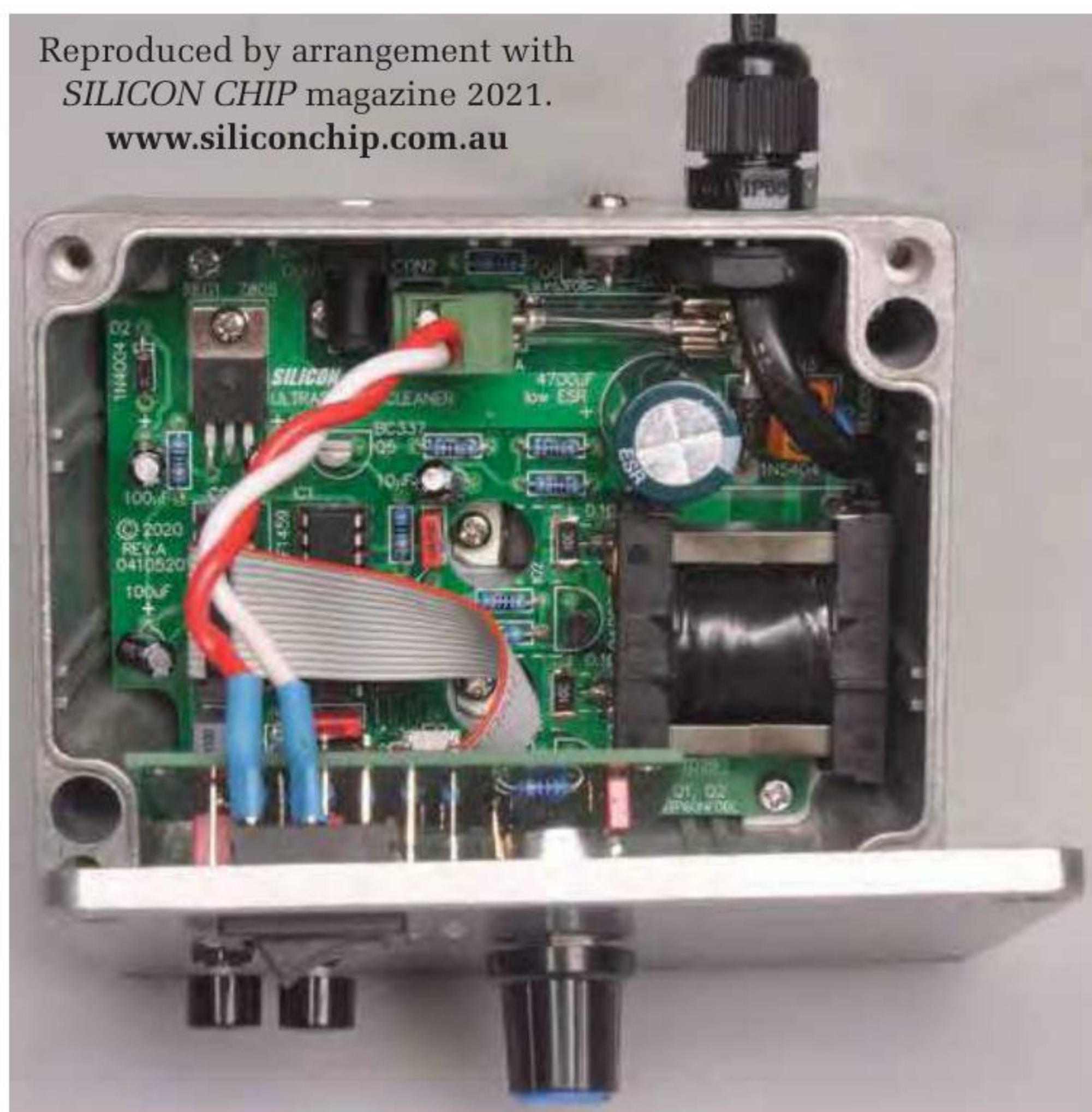
12V DC power for the circuit is fed in via CON1. It needs 4A minimum. If using a 12V battery, it should be rated at 10Ah or more. Power is switched

by S1, which is wired back to the PCB using a plug-in screw connector and socket (CON2). Power then passes to the 5V regulator (REG1) via reverse-polarity protection diode D2. Linear regulator REG1 provides the 5V required by IC1 and IC2.

12V DC also goes to MOSFET Q6 via fuse F1. This MOSFET is used as a soft-start switch to charge the large 4700μF low-ESR bypass capacitor slowly. Without soft starting, charging

the 4700μF capacitor would cause a substantial surge current. This can blow the fuse or cause a 12V switch-mode supply to shut down.

When power is first applied, Q6 is off and the 4700μF capacitor is not charged. When the Start switch is pressed, the RC3 output of IC1 goes to 5V and this switches on transistor Q5. The gate voltage of P-channel MOSFET Q6 then begins to drop towards 0V as the 10μF capacitor



(Above) *If I knew you were comin' I'd've baked a cake...* these are some of the stainless steel containers we found at a kitchen supply shop which would be ideal for this project. Choose the size and depth which best suits your application.

(Left) This shows what the completed *Ultrasonic Cleaner* will look like when we cover the construction and testing side next month. We'll also show you how to set up your ultrasonic cleaning bath using cheap 'cooking' containers.

charges via the 100k Ω resistor to the collector of Q5).

As the MOSFET begins to conduct, it slowly charges the 4700 μ F capacitor. After half a second, the gate charging is stopped by switching off Q5 and after a 250ms delay. The voltage across the 4700 μ F capacitor is then measured using the AN8 analogue input of IC1.

If the voltage across the capacitor is under 9V (3V at AN8), all the level LEDs flash twice per second. This indicates that either the 4700 μ F capacitor is leaky, or there is a short circuit causing the capacitor to discharge. Power can then be switched off, and the fault investigated.

If there is no error, Q5 is switched back on, to continue charging the gate of Q6. It takes one second for the gate to drop 7.5V below the source, at which time Q6 is almost fully on. After a few more seconds, the gate voltage will be very close to 0V, leaving the full 12V between the gate and source. Zener diode ZD1 protects the gate from over-voltage by limiting the gate-source voltage to -13V.

Reverse polarity protection for the power section of the circuit is via a 4A fuse F1, diode D1 and the integral reverse diodes within MOSFETs Q1 and Q2. These diodes conduct current, effectively clamping the supply voltage at -0.7V and protecting the 4700 μ F electrolytic capacitor from excessive reverse voltage. This current will quickly blow the fuse and cut power.

The bath

The ultrasonic transducer needs to be attached to the outside of a suitable container. This can be made from stainless steel, aluminium or plastic

so that the ultrasonic vibration is efficiently coupled to the fluid. Stiffer materials couple the ultrasonic waves with fewer losses.

Ideally, the bath should have a flat side or base where the transducer can be attached. The bath material also needs to be compatible with the epoxy resin used to glue the transducer to the bath. For our transducer, metals are the most compatible material.

We found a series of 'gastronorms' (kitchenware tray/container) at a kitchen supply shop that are ideal. These are the types of food containers you often see at buffets. They slot into steam tables that keep the food warm, and they are available in various shapes and sizes, with several good options at or near the ideal 4L (four-litre-volume) capacity.

You can get them made from stainless steel, polycarbonate or polypropylene with the first two options being the best.

Just do a quick search in Amazon or eBay for 'gastronorm container stainless steel, 4 Litre,' or similar.

We recommend either a 150mm-deep $\frac{1}{4}$ gastronorm tray (capacity 4L), a 100mm-deep $\frac{1}{3}$ gastronorm tray (capacity 3.7L) or a 100mm-deep $\frac{1}{4}$ gastronorm tray (capacity 2.5L).

The 150mm-deep $\frac{1}{4}$ gastronorm tray is tall and rectangular while the 100mm deep $\frac{1}{3}$ tray is more square and shallow. The other tray is in-between the other two.

You can also get stainless steel or clear or black polycarbonate lids to suit all these, which would be a good idea if you're cleaning with a strong-smelling solvent (especially if you plan to leave the solvent in the bath when you aren't using it).

Larger-sized baths with more liquid will have a reduced cleaning effect compared with smaller containers with less fluid.

The fluid used in the bath can be tap water with a few drops of detergent as a wetting agent. Other fluids that can be used include deionised water, alcohol (methylated spirits, isopropyl alcohol), acetone or similar solvents.

Cleaning effectiveness is greatly enhanced when the fluid is warmed. Filling with around four litres is ideal for the power available from the ultrasonic transducer.

With deeper containers, it might be possible to fill them with less liquid for cleaning smaller items.

However, you would need to recalibrate the unit after each fluid level change, and you might find that it would shut down with less liquid in the tank due to the transducer impedance dropping, and the power delivery going above 40W.

This approach would require some experimentation for successful use. The recalibration procedure will be described later. Note also that you would need to mount the transducer quite low on the container (or on the base) to allow different fluid levels to be used.

Conclusion

Next month, we will present the construction details, including how to wind transformer T1, the PCB assembly steps, wiring it up, encapsulating the transducer, case preparation and final assembly.

We'll also describe the testing and calibration procedures, plus give some hints on how to use the *Ultrasonic Cleaner* most effectively.



Fluke/Philips PM3092 Oscilloscope
2+2 Channel 200MHz Delay TB,
Autoset etc – £250

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LAMBDA GENESYS	PSU GEN100-15 100V 15A Boxed As New	£400	Marconi 2305	Modulation Meter	£250
LAMBDA GENESYS	PSU GEN50-30 50V 30A	£400	Marconi 2440	Counter 20GHz	£295
IFR 2025	Signal Generator 9kHz – 2.51GHz Opt 04/11	£900	Marconi 2945/A/B	Communications Test Set Various Options	POA
IFR 2948B	Communication Service Monitor Opts 03/25 Avionics	POA	Marconi 2955	Radio Communications Test Set	£595
IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA	Marconi 2955A	Radio Communications Test Set	£725
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295	Marconi 2955B	Radio Communications Test Set	£800
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA	Marconi 6200	Microwave Test Set	£1,500
HP8903A/B	Audio Analyser	£750 – £950	Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
HP8757D	Scalar Network Analyser	POA	Marconi 6200B	Microwave Test Set	£2,300
HP3325A	Synthesised Function Generator	£195	Marconi 6960B	Power Meter with 6910 sensor	£295
HP3561A	Dynamic Signal Analyser	£650	Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
HP6032A	PSU 0-60V 0-50A 1000W	£750	Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350	Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
HP6624A	PSU 4 Outputs	£400	Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
HP6632B	PSU 0-20V 0-5A	£195	Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
HP6644A	PSU 0-60V 3.5A	£400	Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
HP6654A	PSU 0-60V 0-9A	£500	Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000	Farnell AP100-90	Power Supply 100V 90A	£900
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA	Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
HP83624A	Synthesised Sweeper 2 – 20GHz	POA	Racal 1991	Counter/Timer 160MHz 9 Digit	£150
HP8484A	Power Sensor 0.01-18GHz 3nW-10μW	£75	Racal 2101	Counter 20GHz LED	£295
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750	Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250	Racal 9300B	As 9300	£75
HP8566B	Spectrum Analyser 100Hz – 22GHz	£1,200	Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
HP8662A	RF Generator 10kHz – 1280MHz	£750	Solartron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325	Solartron SI 1255	HF Frequency Response Analyser	POA
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800	Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750	Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700	Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65



HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA



Marconi 2955B Radio
Communications Test Set – £800



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Night Keeper Lighthouse

By Andrew Woodfield

The *Night Keeper Lighthouse* briefly lights up the darkness, to keep children's dreams from running aground on dangerous shores. This is an excellent project for beginners; it's easy to build, and you will learn several important aspects of electronic circuit theory.

Many readers will have children or even grandchildren who from time to time gaze enquiringly at electronic parts and gizmos you're working with on the bench.

At moments like these, it's useful to have a simple project available to encourage the next generation to join in, have fun and take up the hobby.

When my grandchildren were planning a visit recently, I was asked if I could help the 8-year-old build 'something electronic'. Does this sound familiar?

Searching for a circuit suitable for children, it's essential that they can build it reasonably quickly, before they lose interest. Equally, it should be useful enough to gain parental approval.

I have had a blinking light circuit running on the shelf above my workbench for several years. I built it while testing some ideas for discrete high-efficiency boost power supplies. The 'rat's nest' of parts was built on a scrap of prototype board. These days, I use it for the occasional end-of-life 1.5V cell. It's a simple way to use up the very last whiff of energy from such near-dead batteries.

Rather than just building a blinking light, I thought I could make it a little more useful and exciting with a few simple improvements. First, I designed a printed circuit board (PCB) to make it easier for children (and parents, grandparents or caregivers) to build. That PCB allowed me to mimic a widely recognisable object, and make it more attractive and interesting.

It also suggested a few other applications, which will be noted later.

This, then, is the *Night Keeper Lighthouse*. Building it is well within the capabilities of a bright 10-to 12-year-old, or perhaps even

younger with some adult assistance. Since a soldering iron is required, they will need close adult supervision and a well-ventilated workspace. A kitchen table with a similar clear workspace of about one square metre is perfect; cover it with a cloth or some cardboard to protect the surface.

Circuit description

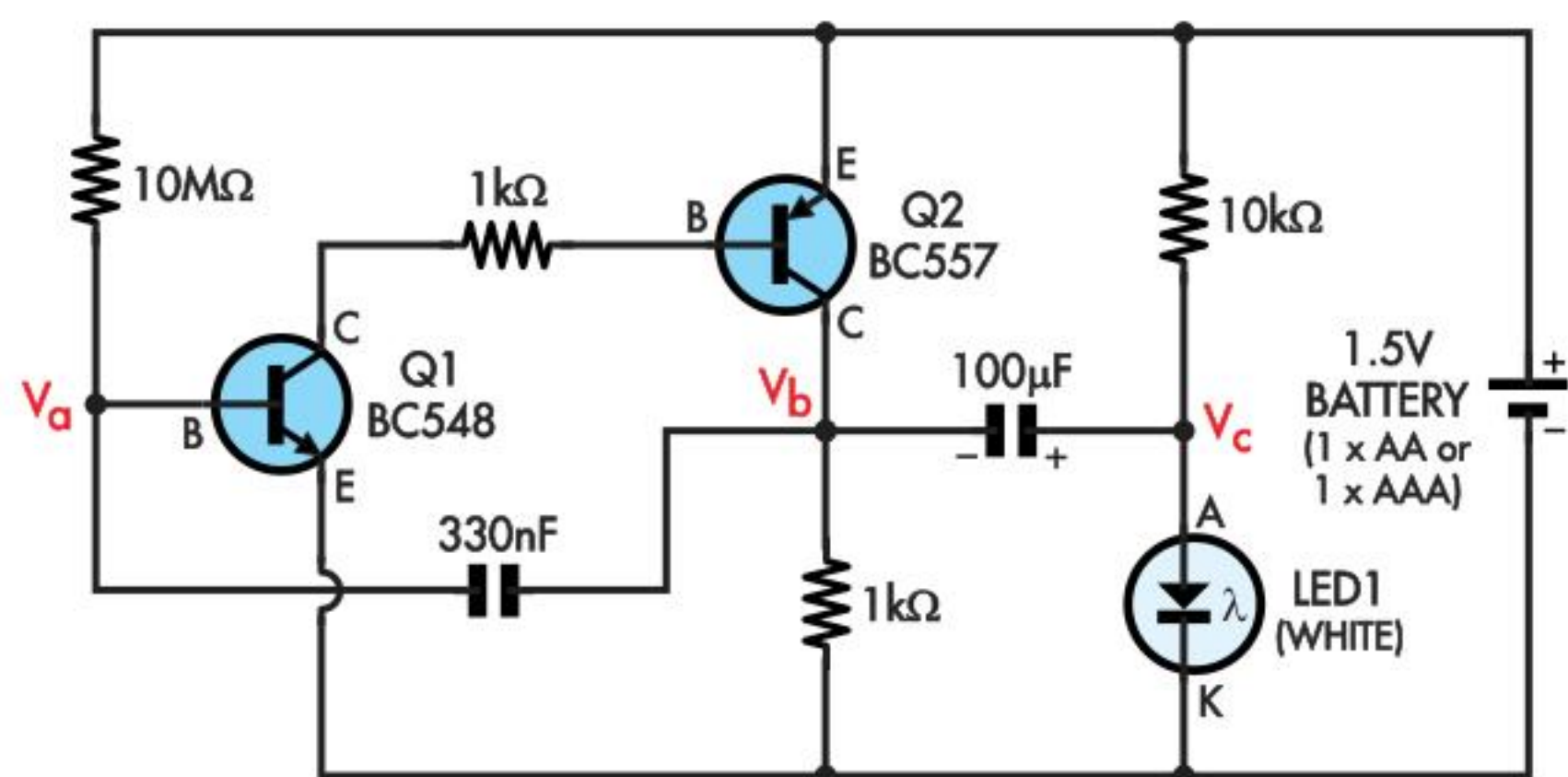
This simple and well-known oscillator circuit (shown in Fig.1) consists of two transistors, a white LED, and a few passive components. It brightly flashes the LED once every second for many months from a single 1.5V cell. Even a near-exhausted battery can power the LED for a month or two.

The two transistors at the heart of the device operate as a highly efficient regenerative oscillator. When power is first applied, the voltage on the base of Q1 (V_a) begins to rise slowly as the 10M Ω resistor charges the 330nF capacitor from the battery. When V_a reaches about 0.6V, the base-emitter junction of Q1, which acts much like a silicon diode, becomes forward-biased and begins to conduct.

Meanwhile, the 10k Ω resistor has quickly charged the 100 μ F capacitor to close to the battery voltage. That's about 1.5V for a new cell. This produces a voltage across LED1 (V_c) very close to 1.5V. However, LED1 cannot light up yet, because white LEDs need more than 2.5V to operate.

As soon as Q1 begins to turn on, its increasing base-emitter current causes its collector current to rise still faster due to the transistor's current gain (beta or h_{FE}) being greater than unity. In turn, this results in Q2's base-emitter junction starting to conduct too. The instant Q2 begins to conduct, voltage V_b starts to rise due to the current passing from Q2's emitter to its collector.





Night Keeper

Fig.1: the *Night Keeper* uses a two-transistor oscillator to drive a charge pump based on the 100μF electrolytic capacitor and the diode junction of white LED1. Once per second or so, the point labelled 'V_c' will shoot up to around twice the battery voltage (about 3V), providing enough voltage to light the LED brightly for a few tens of milliseconds.

Q2 amplifies Q1's collector current still further, as a result of its own current gain. The increasing voltage V_b causes V_a to rise in 'lock-step' as the rise is coupled through the 330nF capacitor. This triggers a swift 'avalanche' effect through Q1 and Q2, causing them to both switch on fully as a result of their combined current gain.

Consequently, the voltage at V_b rises suddenly and abruptly up to the full battery voltage, around 1.5V with a new cell. Since V_b is now suddenly at 1.5V, V_c rises in 'lock-step' via the 100μF capacitor to give about 3V at V_c. This is enough to forward-bias LED1, lighting it up. The charge stored in the 100μF capacitor is then dumped into LED1, giving a brief bright flash of light.

This process is demonstrated in the simulation traces shown in Fig.2. V_a is shown in cyan, V_b in green and V_c in red. The current through LED1 is in blue. You can see that all three voltages rise rapidly at the same time, coinciding with the spike in LED1's current.

While LED1 is lit, the 330nF capacitor keeps Q1 switched on and in doing so, discharges through its base-emitter junction. It manages to keep Q1 on for about 30ms. However, as soon as V_a falls below 0.6V, Q1 begins to turn off. This causes Q2 to abruptly turn off too. The result is V_b suddenly falls from 1.5V to 0V. V_a, via the 330nF capacitor, then drops from 0.5V to -1V.

It goes negative because, just before Q1 and Q2 switch off, V_a is at around 0.5V while V_b is about 1.5V. So when V_b drops to 0V, that is coupled through the capacitor and $0.5V - 1.5V = -1V$.

At this point, the entire cycle begins again. The result is a very efficient regenerative oscillator which produces a brief, but bright flash from the white LED about once every second or two. This is largely determined by the time the

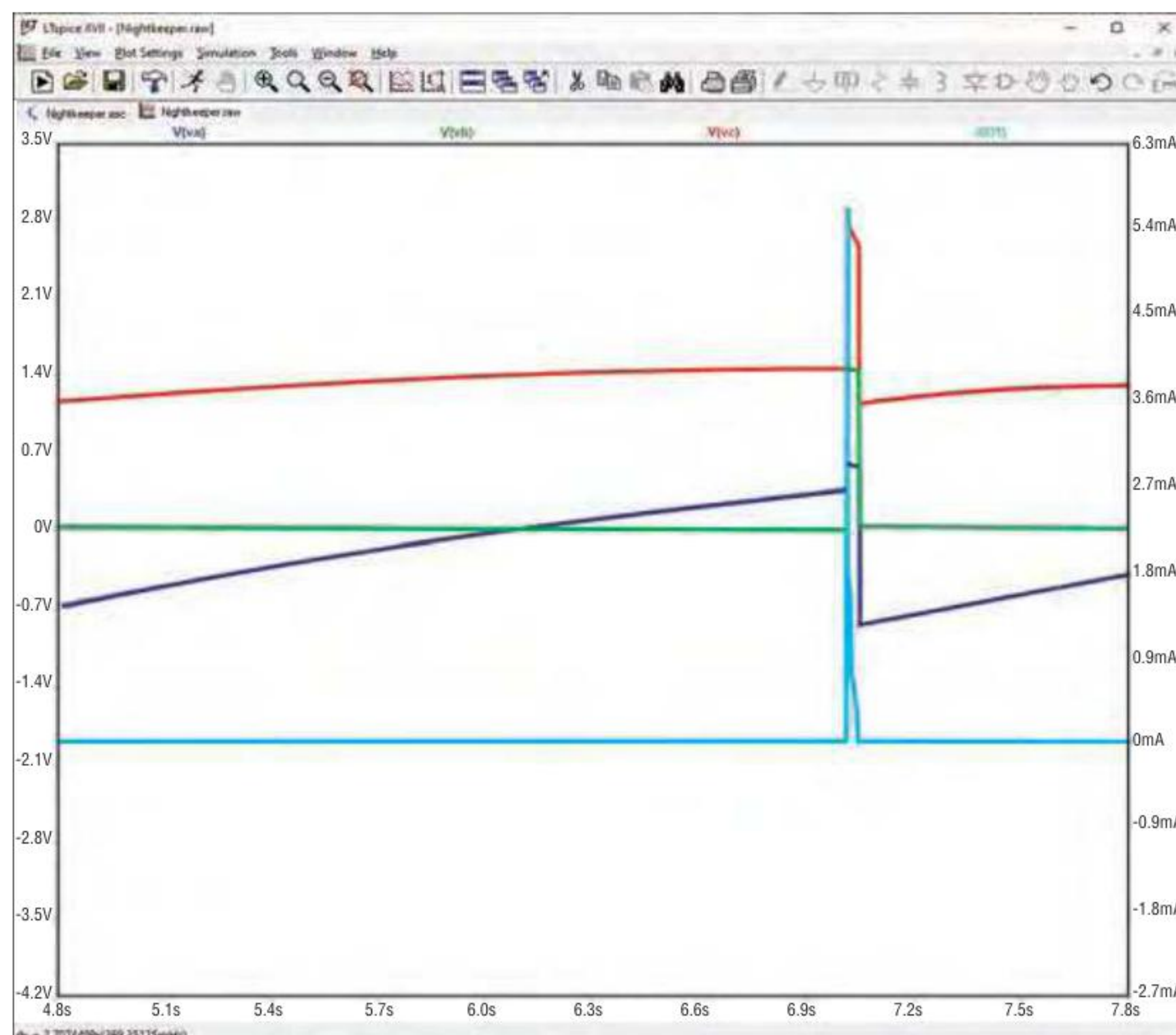


Fig.2: this simulation shows how the voltages at V_a (cyan), V_b (green) and V_c (red) in Fig.1 change over time. V_a ramps up, and then all three voltages suddenly shoot up, at which point the current through LED1 (blue) spikes, until the voltages drop and the process begins again.

330nF capacitor takes to charge from -1V to about 0.6V via the 10MΩ resistor.

Note that while the parts list suggests BC54x and BC55x types, you could also use a 2N3904, 2N2222 or 2SC1815 for the NPN transistor; and a 2N3906, 2N2907 or 2SA1015 for the PNP. Almost any pair of NPN and PNP transistors will work, but keep in mind that pinouts can vary.

Construction

If all of the parts are ready to hand, the *Night Keeper Lighthouse* should take about an hour or so to build. Expect younger children to take longer. Splitting the build into two parts, fitting the resistors and capacitors in one brief session and the remaining parts in a second, makes construction easier and suits the shorter attention spans of young children much better.

Completing the project with the addition of the battery holder and base could be managed in a brief third session.

The *Night Keeper Lighthouse* is built on a PCB coded 08110201, which measures 64 × 91mm and is available from the *PE PCB Service*. Before starting, snap or cut off the circular base from the side of the lighthouse, and file or sand both edges smooth. It's a good idea to score along the cut line before snapping it. To do that, run a sharp knife along the line joining the small 'mouse bite' holes several times.

Set the base aside for now, then refer to the PCB overlay diagram (Fig.3) and construction guide (Fig.4) to see which parts need to go where. All of the parts, except for the battery

Parts list – Night Keeper Lighthouse

- 1 PCB, code 08110201, 64 × 91mm, from the PE PCB Service
- 1 BC547, BC548 or BC549 NPN transistor
[Jaycar ZT2154 or Altronics Z1042]
- 1 BC557, BC558 or BC559 PNP transistor
[Jaycar ZT2164 or Altronics Z1055]
- 1 5mm white high-brightness LED
[Altronics Z0876E or Jaycar ZD0190]
- 1 100μF 16V electrolytic capacitor
[Jaycar RE6130 or Altronics R5123]

- 1 330nF MKT, ceramic or greencap capacitor
(code 0.33, 330n or 334)
- 1 PCB-mount AA or AAA cell holder [AA: Altronics S5029 or Jaycar PH9203; AAA: Altronics S5051; Jaycar PH9261]
- Glue or double-sided foam tape to fix cell holder to back of main PCB

Resistors (all 1/4W, 1% or 5%) (see overleaf for colour codes)

- 1 10MΩ
- 1 10kΩ
- 2 1kΩ

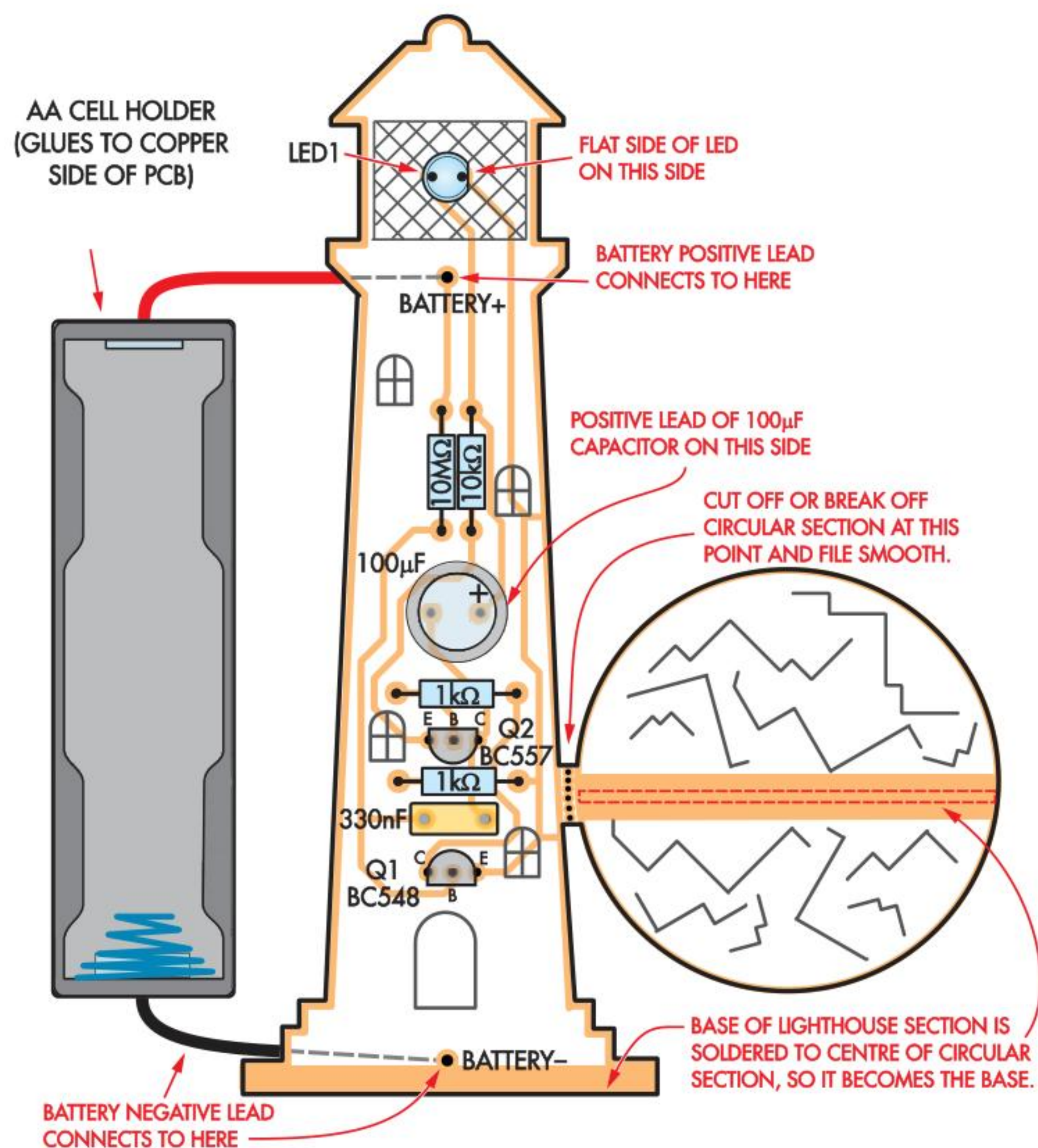


Fig.3: the PCB is made of two parts, the lighthouse itself and its round base, complete with dangerous rocks! Snap or cut them apart before fitting the components where shown here. Rather than attaching the cell holder via wire leads (as shown here, which you could do), we instead recommend mounting the holder on the back of the board.

holder, mount on the top side (the side with the component outlines and part numbers), with their leads soldered on the opposite side. The battery holder is mounted the other way around, and that should be done last.

Begin by fitting the four resistors, which can be identified by the coloured bands as shown. 1% resistors usually have five bands, while 5% resistors typically have four. Both possibilities are shown.

To join the two PCBs together, first 'tack' them with solder and then run a bead of solder along the tinned copper tracks on the PCB. It won't let go in a hurry!



Bend the legs of each resistor in turn with a pair of fine needle-nose pliers or a bending jig, so they neatly fit through the holes for each component in the PCB. Insert them, one by one, in turn, spreading the wire leads apart slightly to hold them in place. They can be fitted either way around. Turn the PCB over and solder both leads to the pads. Then trim off the leads flush with the solder joint using a pair of sharp side-cutters.

Next, fit the 330nF capacitor. It may be either a mylar, MKT or ceramic type. Then install the electrolytic capacitor, and solder and trim the leads in the same manner. Make sure that the longer lead of the electrolytic goes into the pad marked '+' on the PCB. The striped side of the can should be opposite the '+' symbol.

Now it's time to fit the two transistors. Q1 is an NPN transistor while Q2 is a PNP transistor. Each transistor must be fitted in the correct location. They are generally not pushed right down on the PCB, but rather, left with leads sticking out by about 5-10mm. This distance is not critical.

You will probably find it helpful to spread the three leads of each transistor slightly apart before inserting them into the PCB, making sure the flat face is oriented as shown. Once you have pushed the leads through the PCB, spread them apart a little more on that side to hold them in place before inverting the PCB to solder them to the PCB. Again, trim the leads once soldering is completed.

Now mount the white LED at the top of the board. It has a slight flat edge on one side. The LED should be inserted so this matches the shape printed on the PCB overlay for

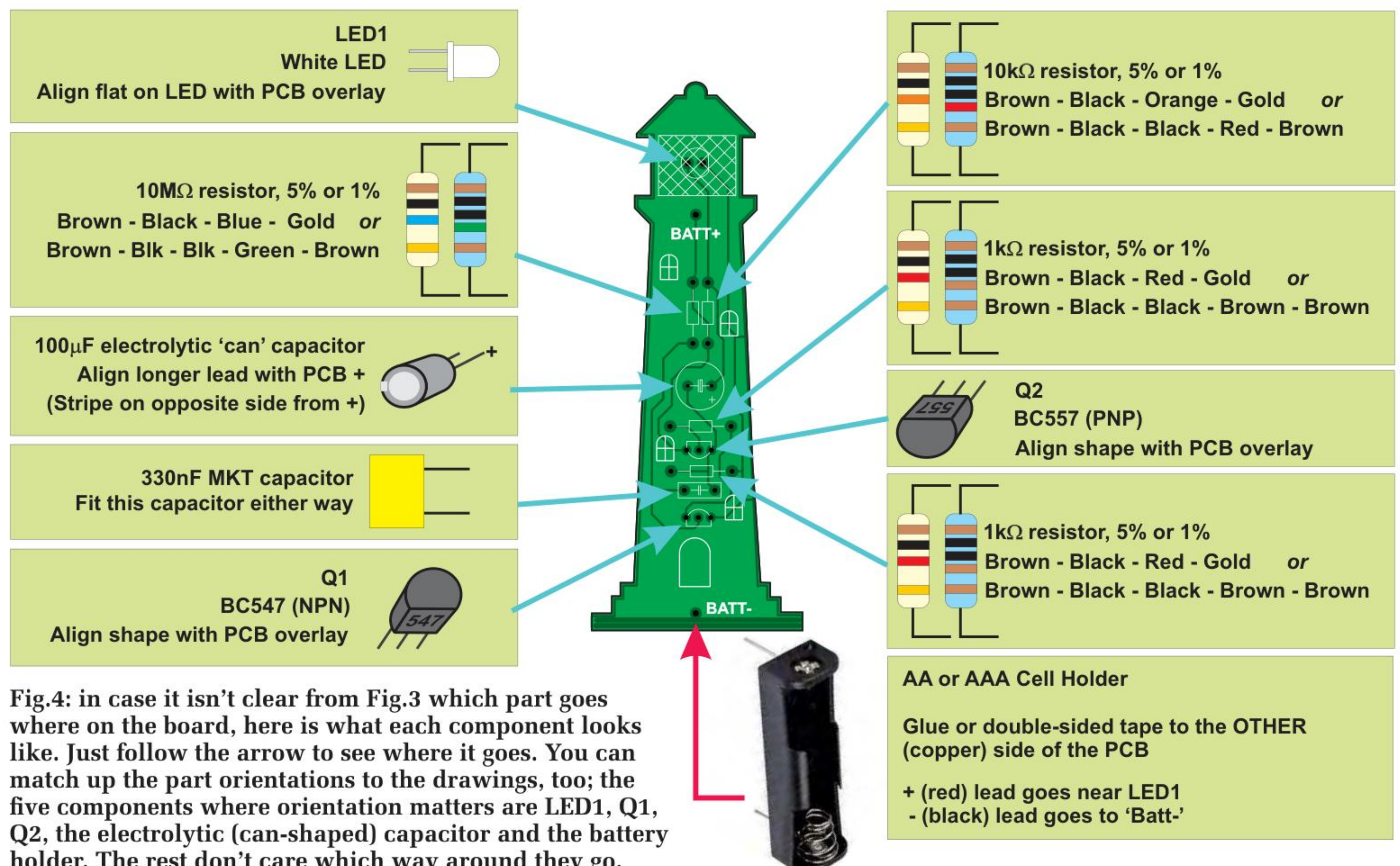


Fig.4: in case it isn't clear from Fig.3 which part goes where on the board, here is what each component looks like. Just follow the arrow to see where it goes. You can match up the part orientations to the drawings, too; the five components where orientation matters are LED1, Q1, Q2, the electrolytic (can-shaped) capacitor and the battery holder. The rest don't care which way around they go.



Here's a side-on view showing the two boards soldered together and the battery holder in position. OK, we cheated a bit: we found that the stiff tinned wire was sufficient to hold it in place without glue or tape.

the LED. The longer anode lead will be on the opposite side to the flat.

Carefully check that all of the parts are correctly located, and that all of the component leads have been soldered and trimmed. Check also that there are no solder splashes which would cause short circuits.

The battery holder can then be mounted on the back of the PCB. A standard AA cell holder is sufficiently large that the end of the battery holder allows the lighthouse to sit on the edge of a shelf or a book, as shown in the photo. The battery provides an ideal weight to hold the lighthouse vertical, useful for tight corners of a bedroom or office.

The wire tails of some battery holders will fit precisely into the holes provided on the PCB. The positive (+) lead should go into the hole nearest the top of the PCB, adjacent to the LED. Other battery holder leads may need to be bent slightly to fit. Use a pair of needle-nosed pliers to bend the wires gently into the appropriate shape to fit neatly.

Ideally, space the battery holder off the conductor-side of the PCB by about 3mm. This provides enough space to solder the two wire connections of the battery holder to the correct pads on the rear of the PCB.

Attaching the base

Alternatively, the circular base PCB can be added. This features a 'rock-like' overlay to add to the overall effect, and allows the *Night Keeper* to be placed on a flat surface. This part of the build may require additional adult assistance to complete – two hands to hold everything in the right place, the other two to apply solder and the soldering iron.

Begin by briefly soldering two small 'blobs' of solder at each end of the lower tinned edge of the lighthouse PCB. Place this on the tinned strip located on the upper surface of the circular base PCB. The main PCB should be approximately central and vertical on top of the base.

Touch the soldering iron to the two 'blobs' of solder to 'tack' the two boards together.

Repeat this if necessary, reapplying the soldering iron briefly to each tacking point while adjusting the main PCB slightly, until the main board is precisely vertical and centred on the base.

Then apply further blobs of solder with the iron along the join, keeping the two boards in their final position.

Finally, run the soldering iron down the tack seam to smooth the join and tidy its appearance.

Operation

Have you noticed that there's no power switch? The circuit uses such a tiny current, a switch is unnecessary. The battery life in use is similar to that of the shelf-life of the battery. A new non-alkaline AA battery can run the *Night Keeper* for over a year.

Hopefully, the faces of the new builders will light up as brightly as the *Night Keeper* just as soon as they insert the battery. As soon as the battery is inserted, the circuit will start to blink.

Note that you could use a AAA battery holder and cell instead of the AA type. In that case, you can expect the cell to last closer to six months. The battery life you achieve



You don't *have* to solder the main PCB to the base: the weight of the AA battery holder will ensure it stays in place 'hanging' over the edge of a bookshelf.

will vary depending on the battery type (heavy-duty, alkaline...) and on its condition when first inserted (new, slightly used or near-exhausted).

Using the Lighthouse

The *Night Keeper* makes a useful bright night-light for children. But keep in mind that flashing lights can disturb sleep, especially if they're aimed at one's face.

Also, because of the brightness of some high-efficiency white LEDs, the *Night Keeper* should not be placed where the LED will shine directly into any young and especially sensitive eyes. It's preferable to locate the *Night Keeper* so that the LED light shines slightly upwards or at right-angles, perhaps onto an adjacent wall. Such arrangements are generally more effective for use as a night light anyway.

Older constructors may find, as I did, that the *Night Keeper* can be useful for locating things in the night, for children and adults alike.

Suitably mounted near a door, a light switch or placed on a shelf, it can help guide your way to a location or around furniture in the depths of the darkest of nights. Just like a real lighthouse!

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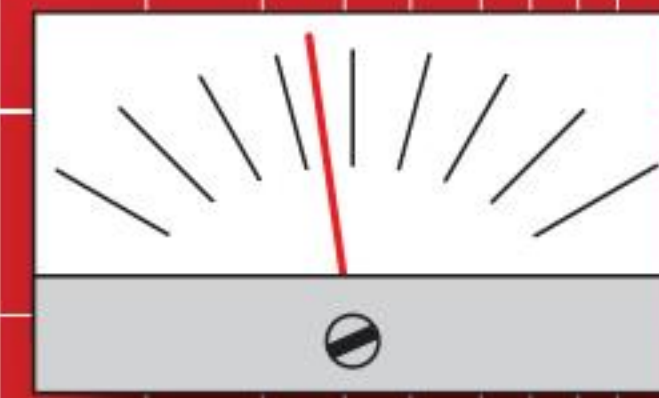
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AUDIO OUT



By Jake Rothman

A question of balance – Part 1

Last month, we finished a marathon, four-part project to produce a high-quality microphone preamplifier. I've used a lot of different mic preamps, and for 'a couple of tenners' this one is as good as many commercial models costing 10 or 20 times as much. An important side effect of this is that it really matters how you connect your microphone to the preamplifier – a few feet of bell wire is definitely *not* the way to go, and so in this and next month's *Audio Out* I am going to walk you through how to build a balanced lead. Even if you don't need a microphone cable, the principles discussed here are applicable to a wide range of audio, and other high-sensitivity analogue circuits.

This month, I'll provide an overview of the technology, especially the ubiquitous XLR connector and I'll also look at the main cable options.

Why balanced?

It's well known that balanced leads reduce noise pick-up in audio systems, but what's the secret behind their success? The key point is that balanced inputs only respond to differential signals; that is the voltage difference between the two signal leads. If the noise or unwanted voltage is

the same on both conductors – such as with induced interference – the voltage difference is zero and the interference is rejected by the input difference amplifier. Thus, the key advantage is the reduction in magnetic interference, both received and transmitted. The basic balanced line set up is shown in Fig.1.

Most balanced audio interconnections use 3-pin XLR connectors, which originally stood for 'extra low resistance'. They are always wired as male for outputs and female for inputs, as shown in Fig.2. (Tip-ring-sleeve (TRS) jack connectors are also used, which are gauge A or B 'stereo' quarter-inch jacks. Occasionally on old US equipment, screw terminal strips are encountered. However, if you are building from scratch then XLR is without a doubt the preferred superior route.)

Phantom power

Sometimes power is applied to a balanced line, as shown in Fig.1. This is used to power microphones and other devices, such as direct injection (DI) boxes. It is normally supplied at +48V and rides on top of the audio. Because it is equal on both signal conductors, it is ignored by the system. The phantom power return current goes back through the screen. It is not ideal, but it is a well-established standard.



Fig.2. Panel/chassis-mount XLR connectors: the outputs are always male (with pins) and the inputs female (with holes).

Earth loops and safety

Unlike unbalanced connections, such as phono, mono jack and BNC leads, the earth



Fig.3. On rare occasions, yellow phase-reverse leads are encountered where hot and cold conductors are flipped. In this case it is a patch cord lead.

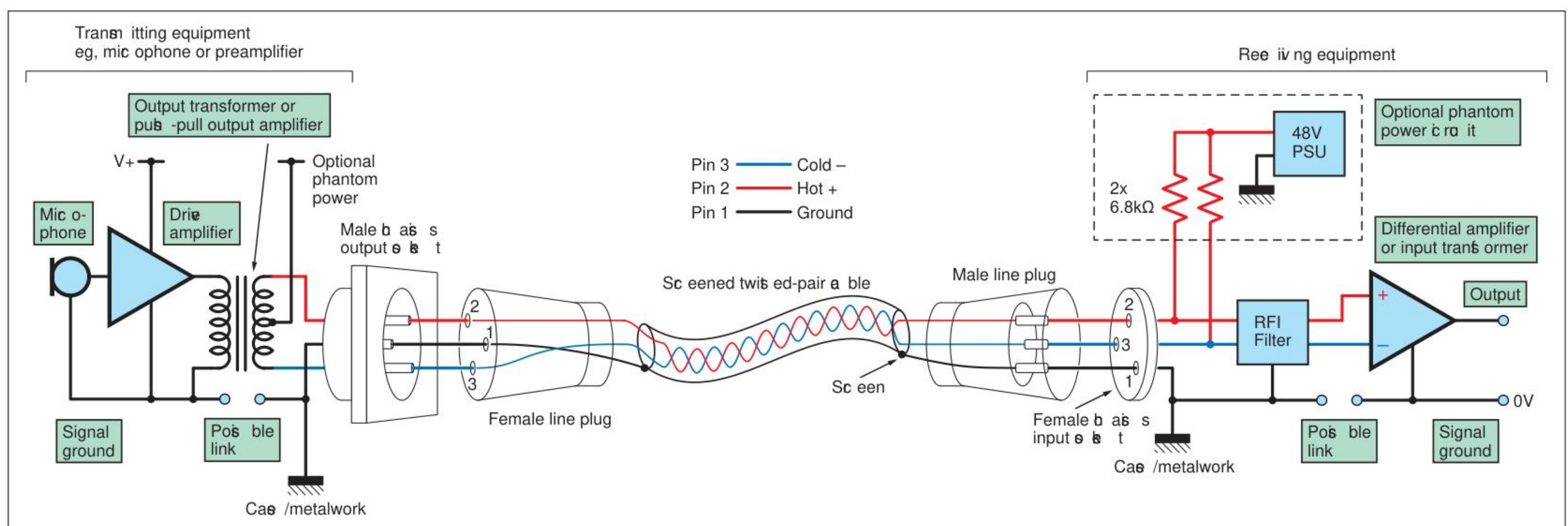


Fig.1. The balanced line system – now standardised except for the ground-lift options, which are inserted in the area marked link. Note also the optional phantom power connections.



Fig.4. An XLR connector earth pin (top right) always connects first because it is a bit longer than the others – what a good idea!

plays no part in signal transmission in balanced connections. In balanced leads, the earth is just for screening; ie, preventing radio frequency (RF) noise pick-up. It has the added advantage that the loud earth-loop hums that can occur in unbalanced systems when more than a few units are connected are avoided. Balanced leads also avoid the worst-case audio scenario where incompetent people try to help by disconnecting mains earth leads from mains plugs. This can lead to metalwork and microphone cases becoming live and sadly quite a few musicians have died through such stupidity.

'The pin-one problem'

It is still possible to get mild earth loops on balanced systems. The balanced system only works perfectly if earths on the balanced connectors are connected to the metalwork or mains safety earth in accordance with the Audio Engineering Society's standard AES48. If they are connected to signal earth, such as 0V on PCBs, the system can still suffer from mild earth loops, since earth currents flowing can then cause voltage drops on the signal ground conductors, thereby impinging on the signal. Audio engineers describe this as 'the pin one problem'. This is because all balanced XLR connectors have always used pin 1 for ground. I spend a lot of my professional life rewiring gear to conform to the new standard. I've often had to carve away ground planes on PCBs to disconnect the signal ground from the metalwork. Note that the RF filter ground should also go to the metalwork ground – *not* the signal ground. The only exception for connecting pin one to signal ground is if phantom power is used. Even this isn't essential if the phantom power supply 0V goes to pin 1.

Ground lift

On Fig.1 there is a link indicated between the metalwork (mains safety) ground and the signal ground. This can consist of several options. Normally, there is simply no

link, in accordance with AES48. On some equipment, such as DI boxes, there is a ground-lift switch. Ground lift is employed to interrupt the currents that circulate in the ground wiring of any system. These currents are the normal consequence of induction from nearby magnetic field sources, such as transformers.

Although ground-lift switches are usually left open, the reason why they are provided is that in any complete audio system, such as a studio, the signal ground and mains ground should be joined at *only* one place. This is normally the most sensitive input point, such as the mixing desk in a studio or the phono input socket on a Hi-Fi system. Having a system with lots of ground-lift switches is a recipe for hum loops. I try not to use them because people randomly flip them. Sometimes, the link is simply a 10nF RF bypass capacitor or a 0.5W 1k Ω ground-lift resistor. The best system is to use both the resistor and capacitor in parallel and do it on the input socket. Possibly a better system (suggested by a reader) is to use two high-current (at least 2A) rectifier diodes in parallel back-to-back which provides $\pm 0.7V$ ground lift and a high-current path for faults. Resistors can burn-up in these circumstances whereas the diodes survive. Ground-lift techniques have not yet been standardised.

One way to avoid these earthing ambiguities is to go completely digital with optical fibre interconnects. However, this introduces a whole new raft of digital set-up problems, such as word clock synchronisation. We won't be discussing that here.

Hi-Fi vs professional

Sadly, balanced leads are not universally used in audio, since they are relatively expensive. They are almost essential when it comes to microphone leads which transmit low-level signals in the order of a few mV and can often be up to 10m long for stage work. For short low-level leads, say around a metre for vinyl record players, unbalanced leads tend to be the norm. In fact, balanced leads tend only to be used by the professional audio community. They are considered unnecessary and undesirable in the minimalist Hi-Fi world. This is because the additional electronic noise from op-amps and resistors on simple differential inputs is significant, while the transformers and extra output amplifiers required also add distortion. The RF interference performance of short balanced Hi-Fi leads is not significantly better than unbalanced ones unless transformers are used and twice as many filtering components are needed.

Blowing hot and cold

Since balanced interconnects are differential, the two signal-carrying conductors are designated 'plus' and 'minus' to signify



Fig.5. The original and still the best – Cannon's XLR connector. Note rubber insert on the female connector.

their phase. In audio technician/roadie parlance, they are designated 'hot' (positive going) and 'cold' (negative going) respectively. XLR pin 2 is hot and pin 3 (the middle one) is cold. Originally, the Americans had it the other way round. Surprisingly, the European convention was formally adopted by the US-based AES. However, audio equipment has a very long life and there is plenty of gear wired with the old system. This often gives rise to unwanted phase inversions. Indeed, it is still so common that many engineers carry with them a phase reversing lead whereby pins 2 and 3 are flipped on one connector. Phase is one of the few areas where two wrongs make a right. These leads are often colour coded yellow, especially in patch cords for patch bays in studios. (Note that with jack connectors (see Fig.3) tip is always plus.)

Commercial XLR connectors

There is a high level of standardisation with XLR connectors. Outputs are always male (with pins), and inputs are always female (with sockets). This means leads can be plugged into one another for extension purposes. One clever feature is that the earth pin always connects first due to the pin 1 socket being slightly longer than the other two, as shown in Fig.4. This prevents those horrid bangs and buzzes one gets with jack and phono leads when they are plugged in and out. There are six different types of three-pin audio XLR hardware: cable plug (male) and cable socket (female); male and female chassis-mount equivalents; and male and female PCB-mount versions.

The original XLR connector was designed by Cannon, later becoming ITT in the US. These are still the most reliable XLRs and are recognisable from their use of resilient rubber for the female connector – see Fig.5. They are no longer made, so I hold on to any that I have. Many are over 50 years old and still work perfectly. Their only problem is that they have three non-standard (US thread) screws which can get lost. Fortunately, I have bags of old spare bits and pieces from my time in the very early 1980s when I worked at Future Film Developments, purveyor of



Fig.6. The Switchcraft XLR connector for those who like a solid 1970s American aesthetic. This is a right-angle version that does not stick out so much.



Fig.7. With Neutrik XLR plugs the case/shell is put on after soldering. Only the cable clamp bush has to go on the lead first. The clamp assembly clips over the cable via a slot. There are no screws, so it's quick to assemble.

parts to the BBC. This was my first proper student sales technician job and where I learnt to be a wireman.

Next on the scene were the Switchcraft Q-G XLRs (Fig.6) which are the best looking, with their bright plated cases and green inserts (the bit of plastic that holds the pins). They have a reverse threaded screw to hold the insert in, it is under the cover and so can't fall out. It has to be turned clockwise to tighten it and it moves up to press on the inside of the case. Q-G stands for quick ground and they are still available from Action Hardware.

XLR connectors were horribly expensive until the Swiss company Neutrik entered the market. These had inferior plastic cable clamps, but only one insert retaining screw. Later models had no screws at all.



Fig.8. Nowadays, both male and female chassis connectors have the same sized mounting format. It's possible to buy ready-punched panels and all sorts of other connectors (eg, USB) to fit the same-sized holes.

A unique aspect of the Neutrik design is that the case is slid on after it has been soldered. These are shown in Fig.7. The chassis connectors were also changed (Fig.8) so that male and female types had the same mounting hole. The mounting holes were also tapped M3. This format was unique to Neutrik for a while, then others followed suit.

XLRs became cheap when the Chinese entered the market, and XLR connectors became a commodity component. Unfortunately, tolerances deteriorated, resulting in some tight-fitting connectors that were difficult to unplug. Some of the plastics used were brittle and cable clamps snapped. To be fair, some commodity XLRs were excellent, but they have to be discovered and stock bought in before the company accountants change things for the worse.

Combined XLR / jack sockets

Neutrik invented a combined XLR and TRS Jack socket shown in Fig.9. Musicians love these because they allow a standard mono jack lead from guitars or semi-pro equipment to be plugged in keeping the show on the road. When using these, pin 1 must go to signal ground.

Cables

The main requirements for a balanced cable are screening and to have two inner cores. These cores need to be twisted together to minimise magnetic field pick up and radiation. There are several different types of screen available:

- **Foil** – 100% screen coverage, but it breaks when moved frequently and is only suitable for fixed installations in equipment, studios and patch bays. The foil is connected by a drain wire and is thus very easy to solder up. A Belden foil cable is shown in Fig.10.
- **Lapped** – 77% coverage and screen can open up in places over time. This is shown in Fig.11. It's easy to twist and solder though. There is also a double-layer version called Reussen screening, with the laps wound in opposite directions.
- **Conductive plastic** – here the screen is a soft semi-conductive carbon-loaded vinyl sheath which gives low movement noise by dissipating static charges. Unfortunately, the resistance is high and a simple drain wire is not good enough. However, combined with a lapped copper screen this can give excellent performance and easy preparation. Fig.12 shows a semi-conductive cable for guitars.
- **Braided** – This is the best giving greater than 94% coverage while being very long lasting with repeated flexing. It is fiddly to unpick and twist into a solderable length. Fig.13 shows how a pointed tool is needed to carefully 'comb' it out, rotating as you go round.



Fig.9. Combined TRS jack and XLR socket – these are useful for musicians who forget to bring the correct leads.

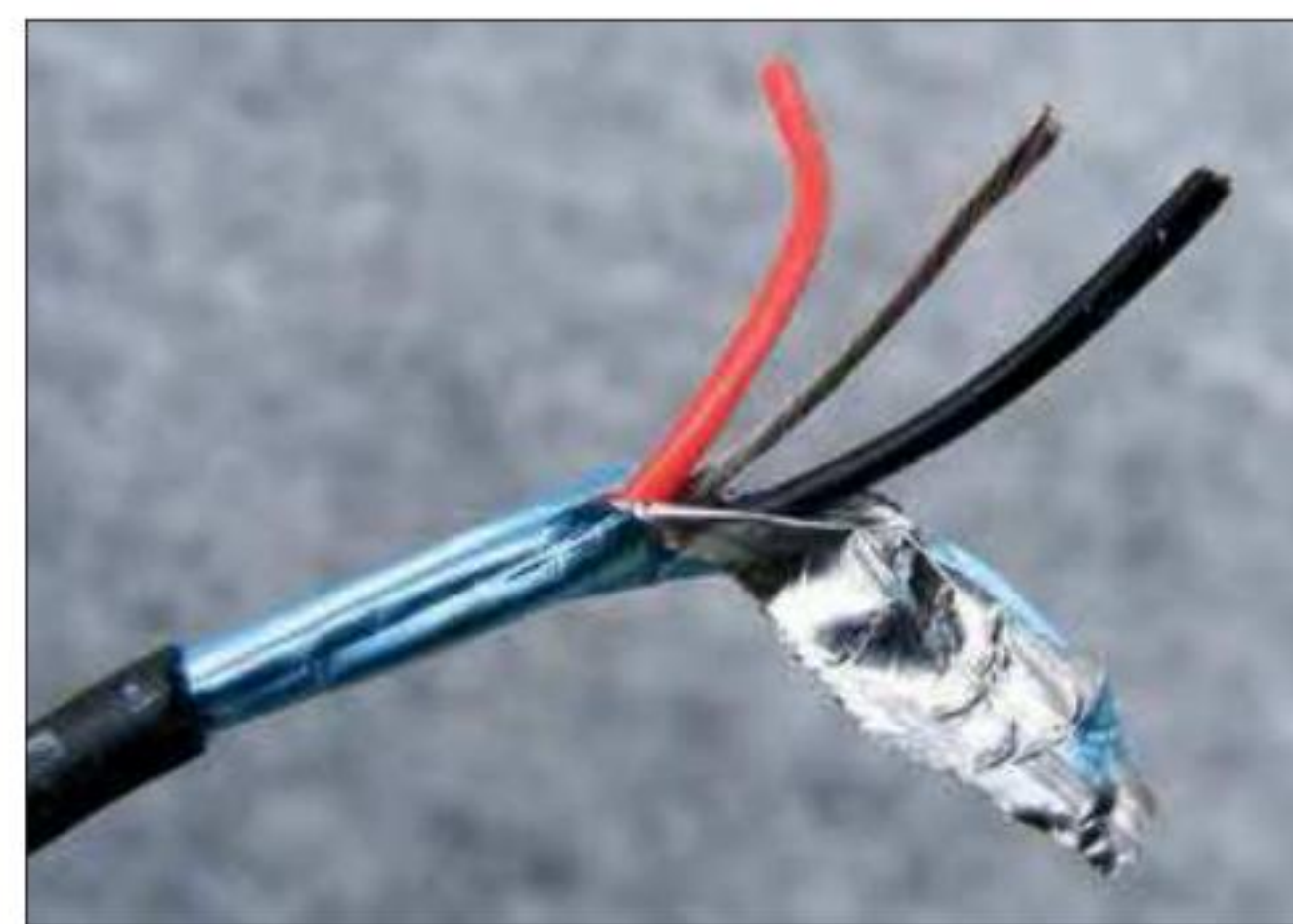


Fig.10. Foil-screened cable used in fixed studio wiring is quick to prepare.

A bradawl will work, but I find the best tool is a dental probe. Some technicians just push the braid back, punch a hole in it and pull the conductors through. However, with dense braids, such as those used by Canare (Fig.14) such an approach, along with cutting the outer insulating sheath too deep, is a recipe for broken strands, which can lead to braid damage – see Fig.15.

Special cables

Most audio signal conductors use polyethylene conductor insulation for its low capacitance properties. Unfortunately, this easily chars at a low temperature and has bad insulation meltback when soldered. Irradiated polyethylene is much tougher. In fact, low capacitance is not vital for microphone and line level cables, since the source impedance is quite low. Therefore, PVC, which gives higher capacitance is fine. However, for high-impedance sources, such as magnetic cartridges in record decks and electric guitars, low capacitance cable insulation is essential.



Fig.11. Lap-screened cable is easy to unwind and solder up.

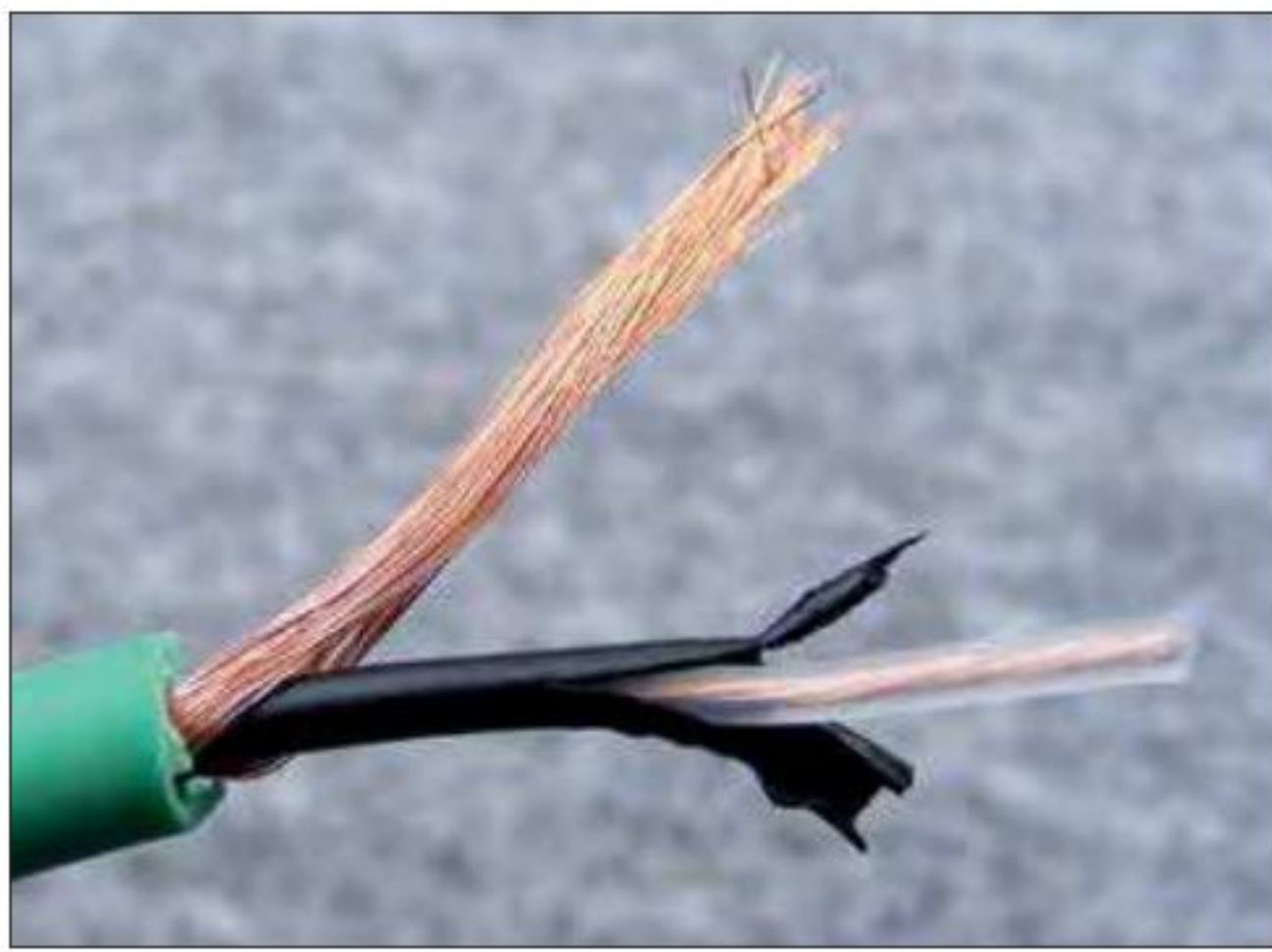


Fig.12. Some screened cables have a semi-conducting plastic sheath (always black) which reduces handling noise. This cable only has one core for unbalanced use.



Fig.13. Braided screened cable is the best but requires labour-intensive combing out to enable it to be twisted and soldered properly.

Tinsel

This is a special type of wire with string on the inside to take the strain, while the copper conductor is wound around it. This gives long life with repeated flexing, such as in headphone, patch and boom microphone leads. It is a pig to solder because the string burns, contaminating the joint.

Star quad

This cable takes the core twisting and magnetic-field cancellation to new levels



Fig.14. Stripped cable exposing the screen braid.



Fig.15. Damaged braid due to careless stripping.

and gives a ten-fold (20dB) improvement in interference rejection. This is the result of implementing a special twisting of two parallel pairs that put the magnetic centres of both signal conductors bang in the middle of the cable. On a normal twisted pair, the centre jiggles about a bit. Comparatively, the residual differential voltage induced by magnetic interference is down by a factor of ten in Star Quad cables and thus there is less for the differential input amplifier to reject. On top of its superior interference rejection, it is also best cable physically, having a supple 'jelly' feel which never gets tangled. Originally made by the Japanese company Canare, it is the best microphone cable available – Canford Audio still sell it. Cheaper alternatives are Van Damme XKE and Mogami. The cheapest StarQuad type of cable I have found is Pro Power STAR00100 with a lapped screen (order No CB13301 from: <https://cpc.farnell.com>).

When Future Film was the exclusive distributor for Canare cable, we had a special demonstration machine built into a briefcase consisting of a triac-based light dimmer and a sensitive audio amp. The lamp cable ran parallel to the XLR cable under test. The buzz was always noticeably less with the Star Quad. When purchasing cable, be careful: 'Star Quad' is now a generic term to cover this particular four-core conductor geometry, as shown in Fig.16. Along with the extra two cores to prepare, terminating Star Quad is labour intensive (see Fig.17). Note also that it has 50% higher capacitance than normal microphone cable.



Fig.16. Star Quad cable has four cores and has better rejection of magnetic fields.



Fig.17. Correct termination of Star Quad cable onto XLR. The same-coloured cores are paralleled. Note: blue is the 'cold' conductor.

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Flashing LEDs and drooling engineers – Part 19

I'm so excited I want to run round in ever-decreasing circles shouting, 'Don't Panic!' I first read the seminal *Foundation* trilogy (*Foundation*, *Foundation and Empire*, and *Second Foundation*) by Isaac Asimov when I was a young lad, and I've re-read them on multiple occasions ever since then, but never did I dare to hope that these masterpieces would one day be brought to life on the big (or small) screen. So, you can only imagine my surprise and delight when, earlier this year, I became aware that Apple TV+ was working on the *Foundation* TV series. Even better, just a few moments before I started penning these words, I heard that this series is set to launch on 24 September 2021. Now, all we have to do is wait in antici...

...pation! What we need is something to take our minds off things as we wait. I know what we can do. While we are twiddling our thumbs, we can pass the time talking about 21-Segment Victorian displays and *SMADs* (*Steve and Max's Awesome Display*) boards.

God save the Queen!

Let's start by reminding ourselves that Steve Manley in the UK and your humble narrator in the US are both creating 10-character versions of the 21-segment

Victorian displays we introduced in earlier columns (*PE*, July and August 2021). The patent for the original display was first filed in 1898 when Queen Victoria was the ruler of all she surveyed (and quite a lot beyond her window). In those days of yore, the illumination was provided by 21 small incandescent bulbs, while the control was afforded by a cunningly complicated contrivance of electro-mechanical complexion. In our case, each display segment boasts one or two tricolour LEDs (Fig.1), while our control functions will be afforded by a microcontroller.

It goes without saying (but I'll say it anyway) that our displays are going to boast myriad capabilities, including being able to react to random sounds and music, but much of the time they will be presenting alphanumeric information such as the time, date and a variety of text-based messages.

Is that the time?

So, what can we do with 10 characters? Well, one obvious application is to display the time in hours, minutes, and seconds along the lines of 08:16:20. In this case, we require only eight characters (six numbers and two colons), which we could centre on the display (Fig.2a).

One of the options we will provide is to present the time in 12-hour (eg, 08:16:20) or 24-hour (eg, 20:16:20) formats. The abbreviation AM (or am or a.m.) stands for 'ante-meridiem' (before the Sun has crossed the meridian line), while PM (or pm or p.m.) stands for 'post-meridiem' (after the Sun has crossed the meridian line). Now, I don't know about you, but I'm usually cognisant as to whether I'm currently in the AM or the PM, so I'm reasonably confident in my ability to work things out if my time is displayed

in a 12-hour mode. On the other hand, some users may prefer a more explicit presentation, and we always have to remember that things could become somewhat confused in the event of a zombie apocalypse, so we could also offer the option to indicate 'A' (AM) or 'P' (PM) while in 12-hour mode (Fig.2b).

Want a date?

When I was a kid, my parents used to serve a variety of nibbles to visitors over the Christmas holidays. In addition to a selection of nuts and pastries, they also used to serve dates. Since I only saw these tasty treats once a year, and as I was aware they originated in exotic Middle Eastern climes, I thought that these sweet fruits were really, really special, but that's not the sort of date we're interested in here.

When it comes to presenting the date in a chronological sense, the format I use with regards to naming files and folders on my computer is YYYY/MM/DD with leading zeros as required (eg, 2021/09/01) (Fig.2c). For a variety of reasons this is the most logical format to employ, which probably explains why its usage is relatively uncommon (humans; bless their little cotton socks).

The next logical alternative is to flip things around and use DD/MM/YYYY, which places the values in order of immediate significance to the viewer (Fig.2d). Finally, for reasons that escape my powers of description, we have the MM/DD/YYYY format that is commonly used in the US (Fig.2e).

It obviously makes sense for us to offer our users the ability to select between the three aforementioned formats when

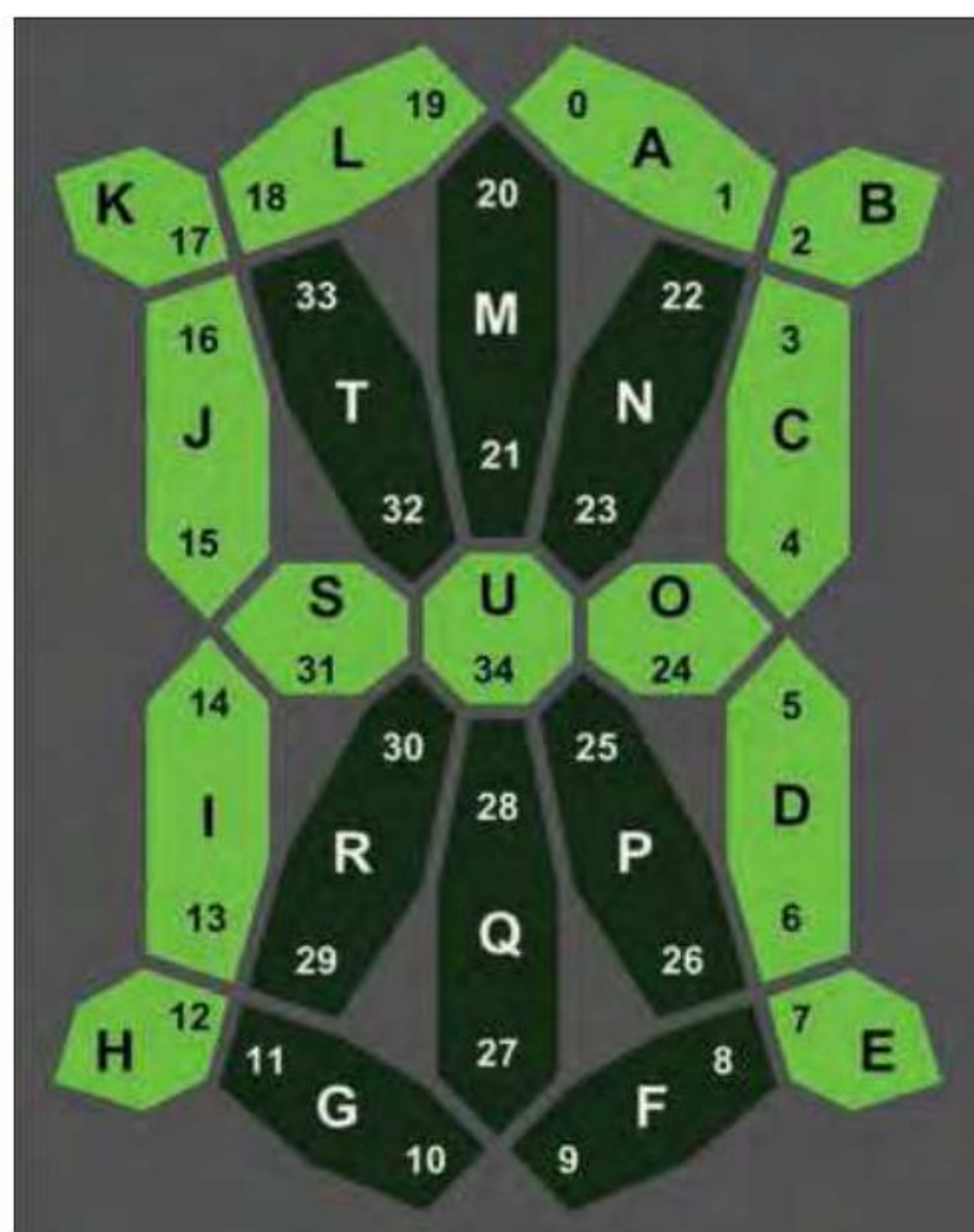


Fig.1. Map of LEDs (numbers) and segments (letters) (Image source: Steve Manley)

(a)		0	8	:	1	6	:	2	0	
(b)	0	8	:	1	6	:	2	0		P
(c)	2	0	2	1	/	0	9	/	0	1
(d)	0	1	/	0	9	/	2	0	2	1
(e)	0	9	/	0	1	/	2	0	2	1

Fig.2. Time and date format alternatives.

(a)	2	0	2	1	/	0	9	/	0	1
(b)	2	0	2	1	/	0	9	/	0	1
(c)	2	0	2	1	/	0	9	/	0	1
(d)	0	9	/	0	1	/	2	0	2	1
(e)	0	9	/	0	1	/	2	0	2	1
(f)	0	9	/	0	1	/	2	0	2	1

Fig.3. Alternative ways of setting the date.

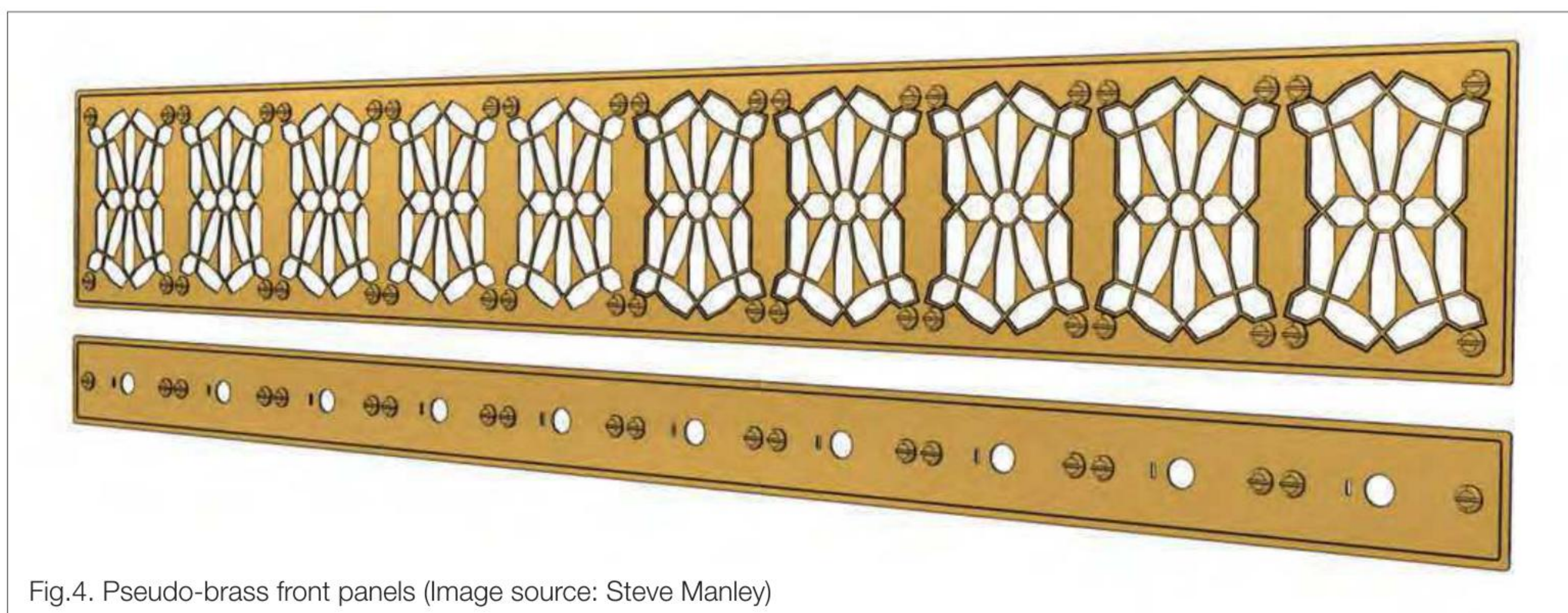


Fig.4. Pseudo-brass front panels (Image source: Steve Manley)

it comes to displaying the date, but this leads us to consider how our users are going to set the date in the first place. On the one hand, we could allow the user to enter any old values in any old order, setting the day to be 66 and the month to be 42, for example, but that really doesn't make much sense. What does make sense is to allow (force) the user to enter only valid values.

Since the number of days in the month depends on which month we are talking about, this means that we must persuade the user to specify MM before DD. Similarly, since the number of days in February depends on whether or not we are in a leap year, it makes sense for us to force the user to enter the date starting with YYYY followed by MM followed by DD.

Let's assume that the user has previously specified that the date should be displayed in the American MM/DD/YYYY format (Fig.2e). One solution when it comes to setting the date is to revert to the YYYY/MM/DD format and guide the user to enter the values in the correct order (Fig.3a, 3b, 3c). For example, we could implement a cursor effect by flashing the current character of interest (CCOI). Or we could make the CCOI bright while dimming the other characters, or we could make the CCOI one colour and the other characters another colour, and – of course – we could use any combination of these effects.

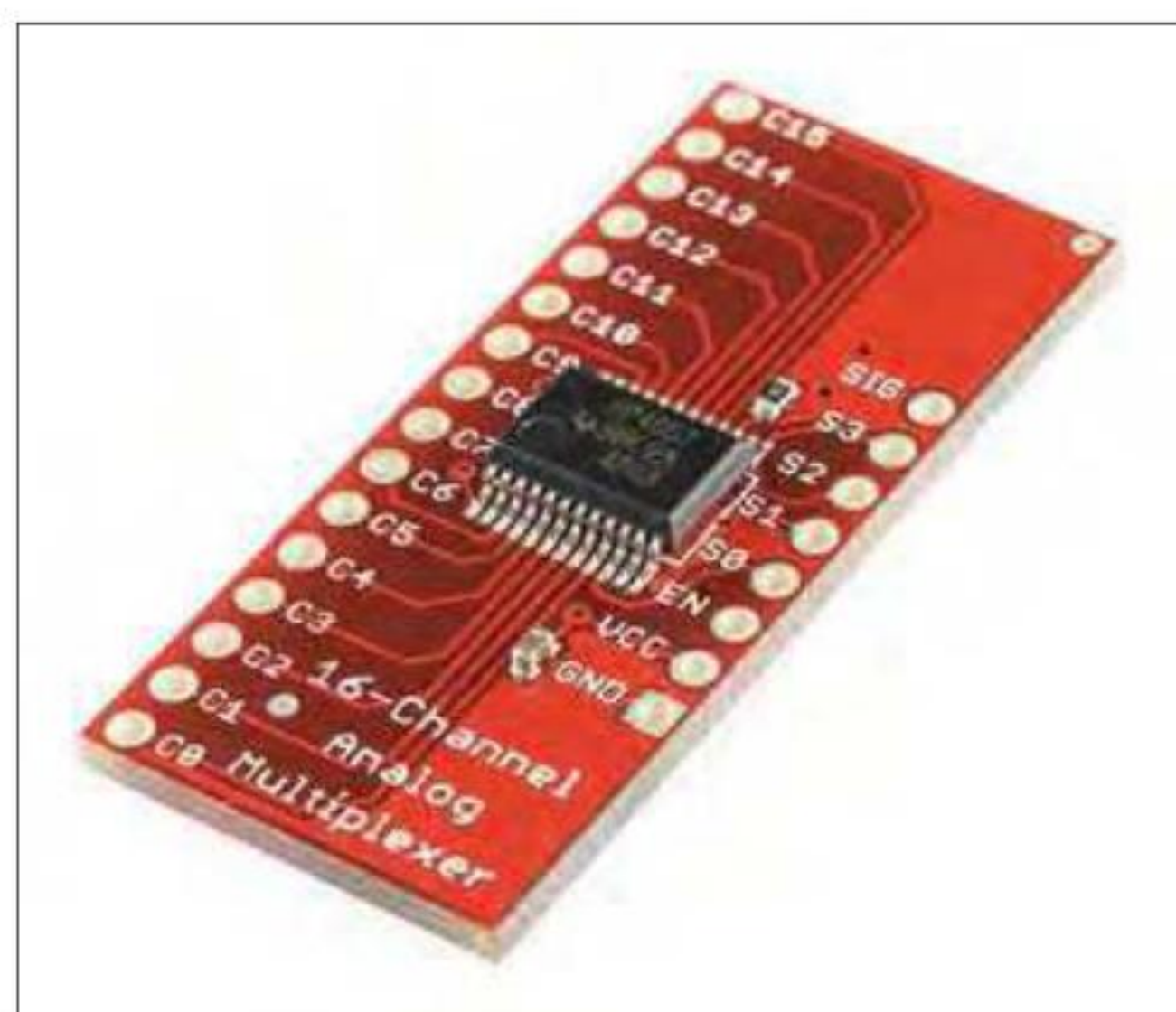


Fig.5. Analogue/digital multiplexer (Image source: SparkFun)

On the other hand, if the user has expressed a preference with regard to the way in which the date should be displayed, who are we to compel them to use a different format when it comes to setting the little rascal? Using any combination of the cursor techniques we just discussed, we could leave the display in MM/DD/YYYY mode while still guiding the user to enter the new date in the order YYYY then MM then DD (Fig.3d, 3e, 3f).

Can you think of another possibility? I just did. My alternative suggestion is at the end of this column.

Why, oh why?

You may be wondering why we are talking about things as mundane as displaying and setting the date and time. Well, the problem is that a lot of people don't take the time (no pun intended) to think this sort of thing out before they leap into the implementation. As an example, I have yet to successfully set the clock in my new (2019) car. I've perused and pondered the manual and I've fought my way through myriad layers of nested menus, but successfully updating the display has defied me. It shouldn't be so hard. I'm the leading engineer in my generation* for goodness' sake (* should you doubt this statement, may I refer you to my dear old mother who will be delighted to help you see the error of your ways).

The point is, at some time in the future, you may end up creating some sort of system that has to allow the user to set and display some form of information. My hope is that our discussions here will aid you in your endeavours and make the radiance of your users' smiles lighten your life.

I #### YOU

I don't think I've shown you a representation of the two laser-cut pseudo-brass front panels I'm using as part of my 10-character display (Fig.4).

Steve wasn't interested in the bottom panel, but he kindly created the design files for me, after which my chum Kevin McIntosh, who is the owner of The Laser Hut in the UK (<https://bit.ly/2RqQ1Zj>), used his laser to cut them out for me.

So, what's with the bottom panel? Well, some time ago I was introduced to an interesting article and video showing a piece of word art that was created by Matt Gorbett in 2007 (<https://bit.ly/2THZLQf>). This piece involved eight characters and two spaces that spelled out 'I #### YOU' (when you include the spaces, this would consume all 10 of the characters in my display).

In Matt's implementation, there are four potentiometers located below the four #### characters. Passersby can use the potentiometers to select letters to complete the message, such as 'I LOVE YOU'. After some period of time, the system starts swapping individual letters to form related messages until eventually returning to its 'I #### YOU' state.

In my case, in the spirit of over-engineering everything, I decided to have potentiometers associated with each of my characters. Of course, this potentially means I'm going to require 10 analogue input pins on my microcontroller. Unfortunately (or fortunately, depending on your point of view), when purchasing my potentiometers, I didn't pay as much attention to the online ordering system as perhaps I should. As a result, it was only when the little scamps arrived that I discovered they had associated switches. Well, 'waste not, want not,' I thought, but this potentially means that I'm going to require 10 digital input pins on my microcontroller, which means 20 pins in all (sad face).

Fortunately, the clever guys and gals at SparkFun have us covered with a rather cool 16:1 analogue/digital multiplexer breakout board (<https://bit.ly/2TPFY1a> – see Fig.5). Using only four digital output pins on the microcontroller, we can select one of the sixteen analogue signals from

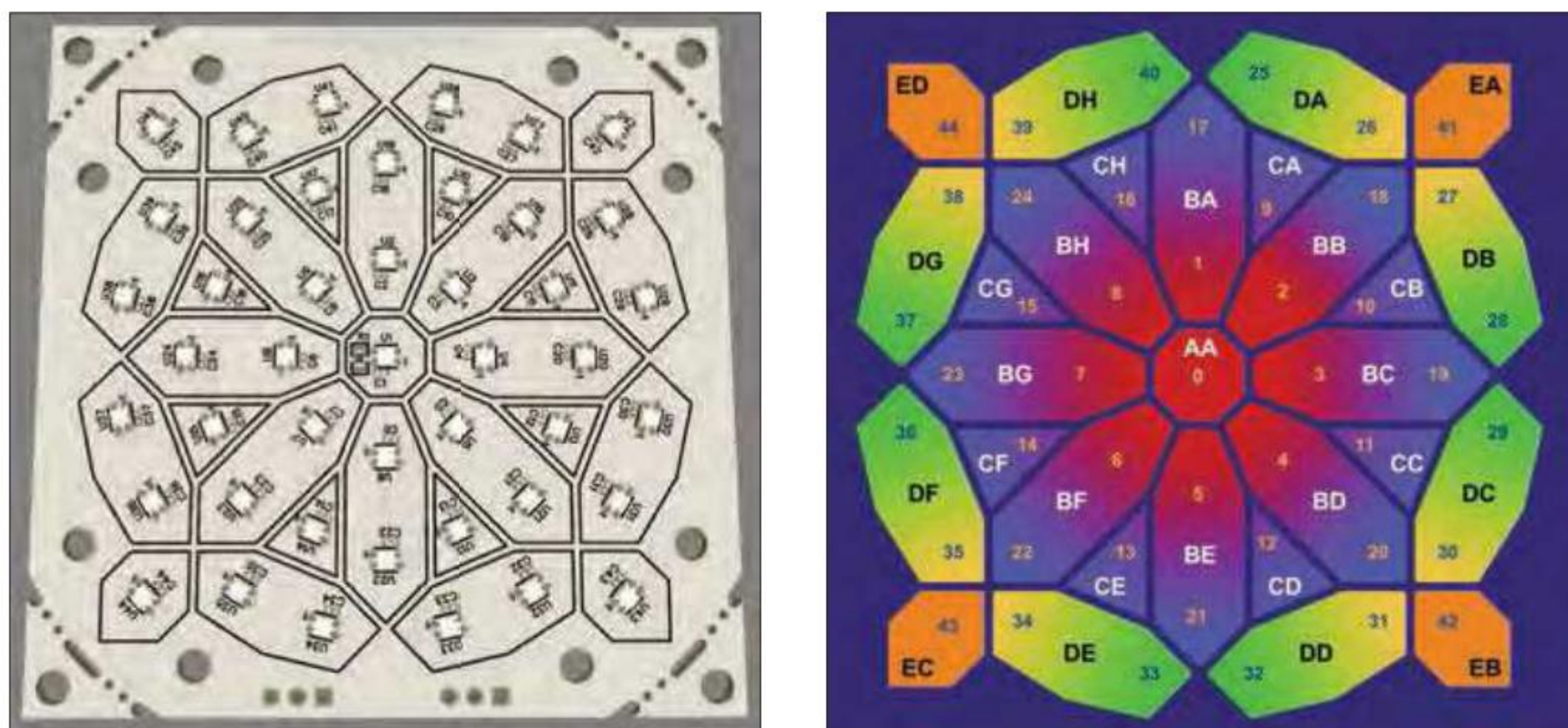


Fig.6. It's a SMAD, SMAD, SMAD, SMAD world: (left) SMAD board, (right) SMAD LED and segment map.

the potentiometers, which we can feed to one of the microcontroller's analogue inputs. If we add a second board, we can use the same four control pins to select one of the sixteen digital signals from the potentiometers' switches, and we can feed this signal to one of the microcontroller's digital inputs. Thus, using only six of the microcontroller's pins, we can read the analogue and digital values from ten potentiometers and associated switches. Pretty cool, eh?

Are you SMAD?

As we discussed in last month's *Cool Beans* (PE, August 2021), creating a full-up 10-character 21-segment Victorian display is a bigger project than most readers care to commence. Also, the software for the little rascal is more complex than we want to discuss here. Our solution was to create SMAD boards, which are available for purchase from the PE PCB Service (<https://bit.ly/3wVUgLq>)

for only £11.95 each, which includes shipping in the UK (shipping outside the UK will be quoted separately).

Each SMAD contains 45 tricolour LEDs (Fig.6 left). Typically, we attach a 'shell' to the front of the board to compartmentalise the light from the LEDs, where these shells can be 3D printed or laser-cut (see last month's *Cool Beans* for more details). Our original shells boasted 29 segments, with 13 segments containing only one LED and 16 segments containing two LEDs (Fig.6 right). However, Steve then decided to experiment with 45-segment shells with one LED per shell, which left us in a bit of a pickle. On the one hand, we delight in the gradient effects that can be achieved by varying the colours of the LEDs forming the dual-LED segments in the 29-segment shell; on the other hand, we relish the stained-glass effect presented by the 45-segment shells. In the end, we decided to use both.

Seeing eye to eye

The wonderful thing about SMADs is that you can create an awesome display using just one board. Having said this, much like eating crisps ('chips' in the US), it's hard to stop with just one. For example, one of the things Steve and I discussed was the possibility of using two SMADs to form the 'eyes' of a pseudo robot head.

Armed with his trusty 3D printer, Steve created what I refer to as his 'Owl Glasses' display. Let's look at an exploded view showing the main frame (orange) and one SMAD (Fig.7). If you want to create your own Owl Glasses display, Steve has kindly made the design files available. A compressed ZIP file containing these design files is available on the September 2021 page of the PE website at: <https://bit.ly/3oouhbl> – file **CB-September21-01.zip** contains the files for the main frame and updated versions of both the 29-segment and 45-segment shells.

Remember that Steve's 3D printed shells come in three parts – the front half, the back half, and the facia. The only reason for splitting the main shell into two halves is to make them easier to paint (use a white primer followed by a gloss white finish to obtain the brightest and most vivid colours).

Also, observe that these shells are slightly different to the standalone versions we discussed in the previous column. Those shells had clear holes for the machine screws used to mount the displays because I like to see the screw heads on my front panels. By comparison, in the case of the shells for the Owl Glasses, the holes in the front shell are threaded (as are the blind holes in the frame) because Steve prefers a no-screw look. Also, there are no screw holes in the facias, which are held in place by small lips in the frame and aligned with an alignment key (as are the shells). In the case of the diffuser, we are employing the white plastic separator sheets you can purchase to use with file folders. (For example, these white polypropylene dividers from Toner Ink Online (<https://bit.ly/3inEODY>) – but of course others will do just fine).

Steve created two versions of his Owl Glasses display – one with 29-segment shells and the other with 45-segment shells (Fig.8). The important thing to note here is that all four SMADs are displaying exactly the same colours. This really illustrates the difference between the larger segments in the 29-segment shells where the colours from two LEDs are diffused together, as compared to the smaller segments in the 45-segment shells where the colours are kept separate.

By comparison, I decided to create two 'robot heads' inspired in part by WALL-E (https://youtu.be/_ksIEYbMr1g – see Fig.9). The white card box in the foreground of

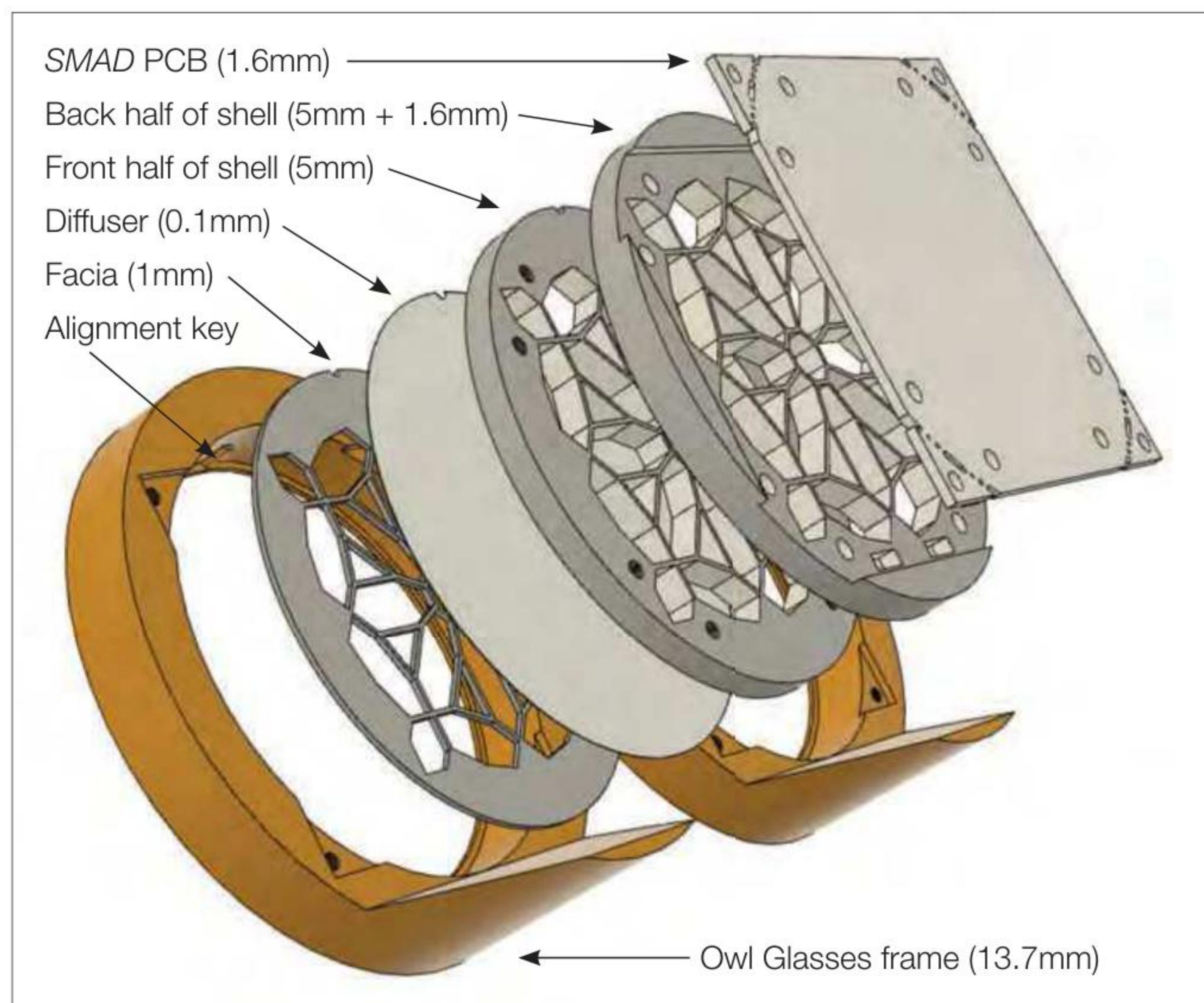


Fig.7. An exploded view of the Owl Glasses display (Image source: Steve Manley).



Fig.8. Two Owl Glasses displays with 29-segment shells (top) and 45-segment shells (bottom) (Image: Steve Manley).

this image is the mockup I created as a prototype. Observe that I've still got to build the overhanging tops and sides for the real heads. Just to vary things up a bit, I decided to have black shells on a nickel-coloured face for one head, and nickel-coloured shells on a black face for the other. I used slotted, pan-head steel machine screws to attach the shells because it matches my 'steampunk aesthetic' (in the case of the black shells, I used 'gun blue' liquid to blacken the heads of the screws).

The very first test

For my very first test, I just wanted to make sure that I could light the red, green and blue channels in each of my LEDs individually (you can see my code in file **CB-September21-02.txt**). Remember that we are using WS2812 LEDs (a.k.a. NeoPixels), which can be daisy-chained together. In my case, I've also daisy-chained all four *SMADs*, thereby giving me a single string of $4 \times 45 = 180$ LEDs. At the top of my sketch (program) you will see the following definitions:

```
#define NUM_NEOS_PER_SMAD 45
#define NUM_SMADS 4
```

Also, I define `NUM_NEOS` as being `NUM_NEOS_PER_SMAD` multiplied by `NUM_SMADS`. This means that you can easily modify this program to work with your own setup comprising one, two, or more *SMADs* by simply changing the value assigned to `NUM_SMADS`.

We introduced NeoPixels in depth in an earlier *Cool Beans* (*PE*, July 2020), but it might be a good idea to briefly remind ourselves as to how these little beauties work in case you are new to the party. First, make sure you have the latest version of the Arduino Integrated Development Environment (IDE) downloaded to your



Fig.9. Two robot heads with 45-segment shells (left) and 29-segment shells (right).

computer from the Arduino.cc website (the current version at the time of this writing is 1.8.15).

Next, make sure you have the latest version of whatever library you wish to use to control your NeoPixels. If you wish to use Adafruit's NeoPixel library, launch the Arduino IDE, select 'Tools -> Manage Libraries,' search for 'Adafruit NeoPixel,' and install the 'Adafruit NeoPixel' entry (don't be lured by the DMA and other options). Alternatively, if you prefer to use the FastLED library created by Daniel Garcia, search for 'FastLED' in the Arduino's library manager. (If you already have these libraries installed, you can use the same mechanism to check to see if they need to be updated.)

When you instantiate your string of NeoPixels (I named my string 'Neos'), you specify the number of pixels in the string and the microcontroller pin you are using to control them (look at my test program for an example).

The act of instantiating the string creates an array in the Arduino's memory. This array contains three bytes for each pixel, where these bytes are used to store that pixel's red, green and blue components specified as 8-bit integers with values from 0 to 255. Suppose we wish to change the colours associated with pixel 6 to be red = 255 (0xFF in hexadecimal), green = 128 (0x80), and blue = 66 (0x42). We can do so by specifying each channel individually using `Neos.setPixelColor(6, 255, 128, 66)` or `Neos.setPixelColor(6, 0xFF, 0x80, 0x42)`. Alternatively, we can specify all three colour components as a single value using `Neos.setPixelColor(6, 0xFF8042)`.

The important thing to remember is that the `setPixelColor()` function doesn't

actually modify the display in the real world. All it does is to change the values in the array stored in the Arduino's memory. It's only when we use the `Neos.show()` function that all the colour values in the array are uploaded into the NeoPixel string and presented to the user.

Good dates

Earlier on, we posed a question as to the best way to set the date on the Victorian display. I seem to have dates on my mind, because I was just reminded of the scene from *Raiders of the lost Ark* when Indiana Jones throws a date into the air and his friend Sallah (on seeing the dead monkey) grabs it and says, 'Bad dates' (see: <https://bit.ly/2UzTgiu>).

Of course, we are dealing with the other kind (ie, good dates). Originally, when it came to setting the date on my Victorian display, I was thinking of the display showing things in the form YYYY/DD/MM or DD/MM/YYYY, or even MM/DD/YYYY, as we discussed earlier. But then it struck me that we have a full-up alphanumeric display capability, which means we can use the display to show, 'YEAR=?' followed by 'MONTH=?' followed by 'DAY=?' and – in each case – simply leave the user to enter the appropriate number and then press the OK button.

Coming soon

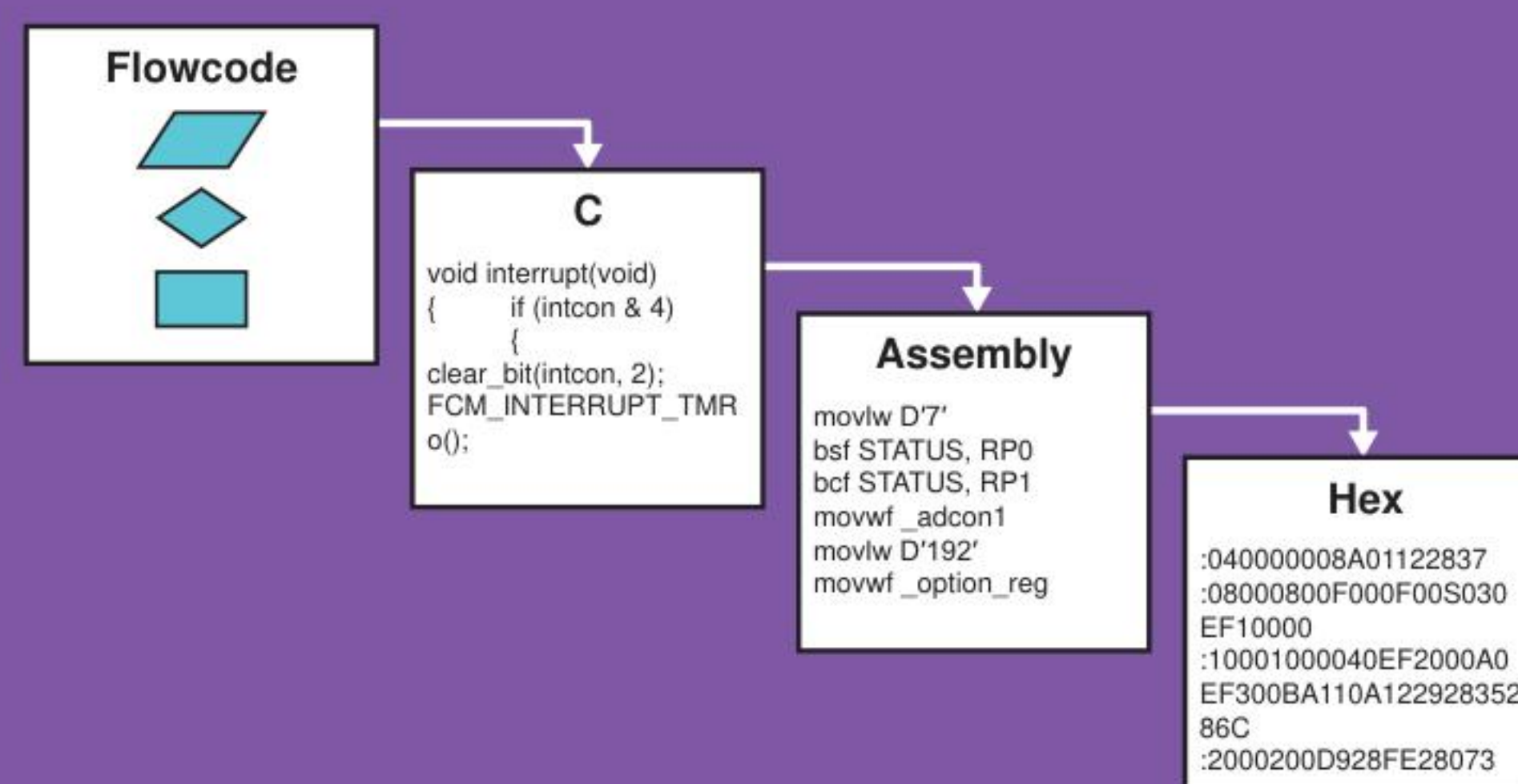
In next month's column we will start to experiment with some of the clever effects we can achieve with our *SMADs*. In the meantime, I would love to see pictures should you decide to create your own robot head or any other form of *SMAD*-based artifact (we might even feature your creation in a future column). Until then, as always, I welcome your comments, questions and suggestions.



Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: max@CliveMaxfield.com

Flowcode Graphia I Programming



Introducing Flowcode

In this article – the start of an occasional series – Martin Whitlock discusses an easy route to programming microcontrollers and avoiding the steep learning curve of writing C code.

Picture the scene. You're reading your favourite electronics magazine – *Practical Electronics*, naturally – and you see a fascinating project that involves a microcontroller IC or board, typically a PIC, Arduino or Raspberry Pi. The source code for running the microcontroller is available for download from the *PE* website and you decide to build it.

Success! The project works and you're pleased with the result, but why stop there? Wouldn't it be great if you could alter the code and make your own tweaks and subtle changes to what the project can do? Unfortunately, at this point you may hit a brick wall. Either the code is only available in hex, and hence not readable/editable, or it's supplied in C, a feature-rich, sophisticated but complicated and time-consuming language to learn, let alone use to edit a program or even write one from scratch.

At this point, you suspect your project-improvement ideas come to an end...

or do they? How about using a software package that makes programming as easy as drag and drop? Flowcode for Windows is one of the most advanced graphical programming languages for microcontrollers (including the later ESP32 ranges). It involves no complex C coding; in fact, you don't need any programming experience to create and develop a complex electronic system in a remarkably short timeframe.

Using Flowcode means you don't need to limit yourself to modifying other people's projects, you can design, build and program your own projects with fully tested and simulated code. Whether you are a complete beginner or an advanced coder, Flowcode's powerful simulator lets you build *and* test your own design before uploading it to your microcontroller hardware.

Drag and drop

So how does it work? Essentially, you just choose the components you would like to use and then 'drag and drop'

them onto a 2D 'dashboard'. Then you link them up. You can include displays (LCD and LED), switches, sensors (for example, to measure temperature and humidity), servo and stepper motors, keypads and a whole host of other parts.

You won't get very far in modern microcontroller design without using communication protocols, and Flowcode works with the most important ones: CAN, RS232, SPI, I²C, One wire, USB Serial, IoT and more. This lets you quickly and easily interconnect sub-systems and peripherals using well-established protocols. Trust us, building a USB interface from scratch is no one's idea of fun, but with Flowcode it is straightforward. All the complexity is taken care of under the bonnet, leaving you to focus on the overall design.

Fig.1 shows the kind of construction you build in Flowcode – in this case, to make a simple decision. As you can see, there's no code involved, just the intuitive use of a flowchart, which of course is why we call it 'Flowcode'.

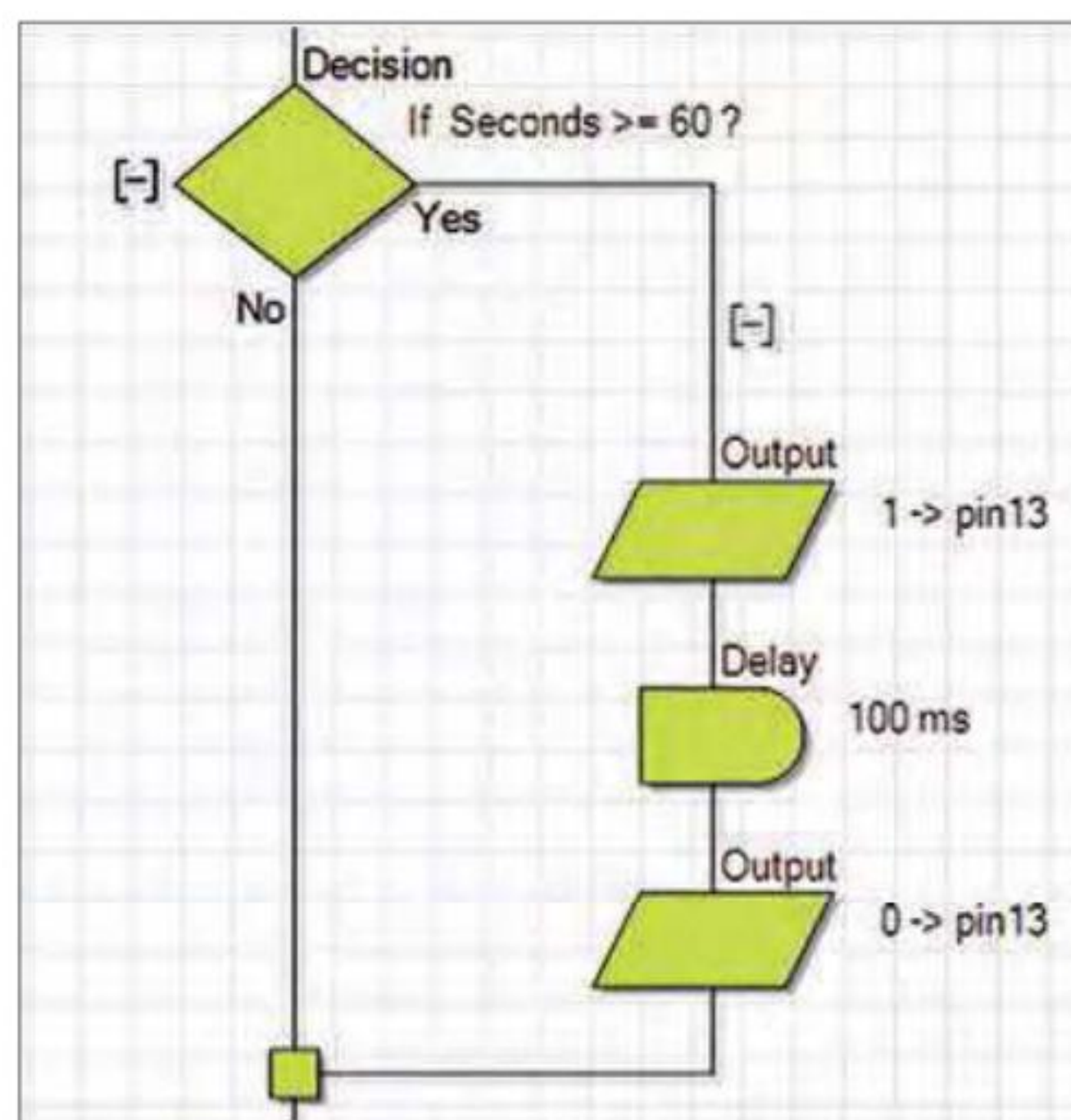


Fig.1. This is the kind of code-free flowchart that is easily generated in Flowcode and which is then used to generate your microcontroller's code.

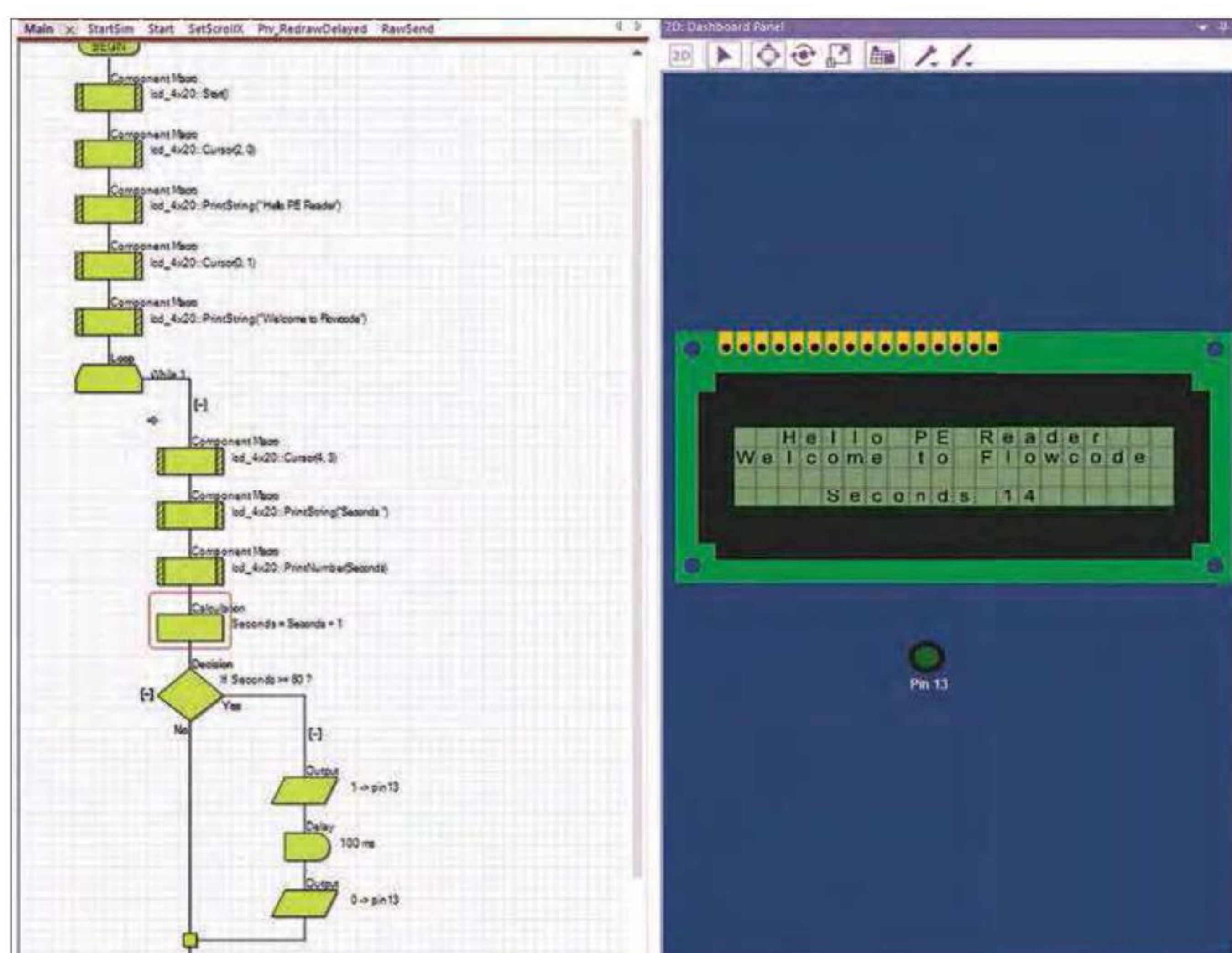


Fig.2. This simple 'Hello World' Flowcode example is quick and easy to set up.



Fig.3. Some of Flowcode's simulation and debug options – we will return to these in a future article when we explain in detail how to use Flowcode.

Design example

When learning a computer language, the classic first program is often a little exercise to write the words, 'Hello World'. Fig.2 shows how you could do this in Flowcode, but with the bonus of displaying the text on a four-line LCD connected to a microcontroller. It also shows the display time in seconds.

Once you've built your flowchart, Flowcode lets you run a simulation to check that it works. This is an important advantage of Flowcode – you can run your program without the extra, time-consuming step of repeatedly uploading it to the microcontroller during the early test-and-design stage. Your simulation will let you check the program's operation quickly and efficiently. To do this, select the Debug Ribbon, which will present you with the options shown in Fig.3.

In Fig.2's simulation you can see from the simulated LCD that our flowchart is displaying our chosen message. In Fig.4 you can also see 'code profiling' in action (the red elements), which is a very useful debugging feature. This

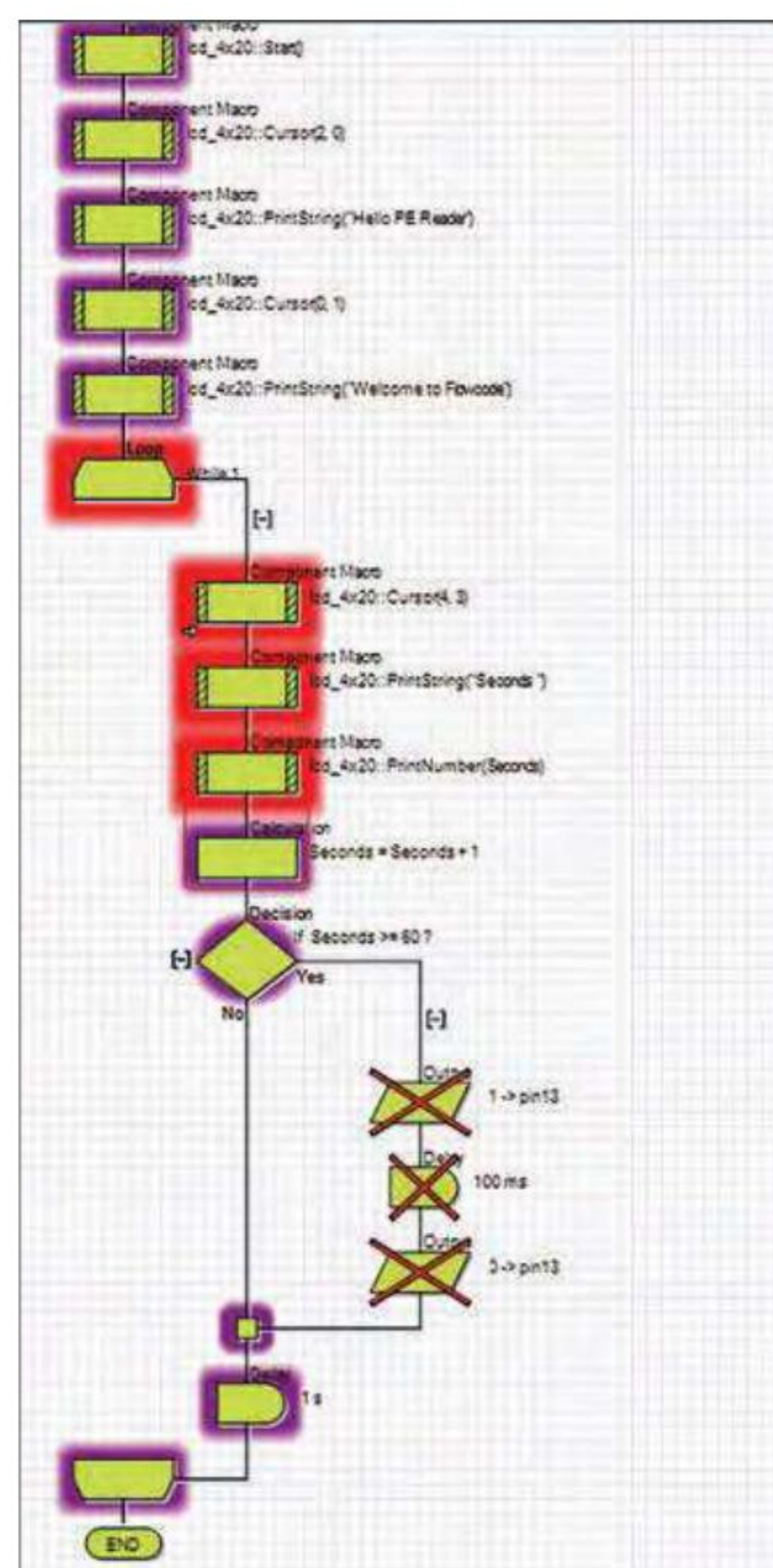


Fig.4. The 'Hello World' program running code profiling during simulation.

lets you check during the simulation which functions are being accessed (or not). This is especially handy with larger, more complex flowcharts, helping you to troubleshoot problems and finetune operation.

Real-world operation

Once the 'Hello World' program was running correctly in simulation, it was time to transfer it to some real hardware – in this case, a Sparkfun RedBoard. These are 100% compatible with Arduino UNO, inexpensive and great for prototyping (see Fig.5). We could have used other hardware – Flowcode works with many of the important ones – but we like this one.

Setting up Flowcode for any target device (the microcontroller) is simple. You will need the drivers for your microcontroller of choice, in this case the RedBoard (these are available from: <https://ftdichip.com/drivers/vcp-drivers/>).

Given the RedBoard's Arduino UNO compatibility, to upload the code, all we have to do is:

- Select the Build Ribbon, Project Options from Flowcode's menus
- Select Free targets in the Choose a Target area
- Scroll down to the Arduino targets
- Choose R3 SMD, but any UNO target will work
- Select the COM port for the RedBoard and Click Modify
- Select the Build Ribbon
- Choose Compile to Target icon

For our example project, the LCD hardware worked the first time – it really is that easy and simple!

Coming up next

This has been a very brief introductory overview of Flowcode – we haven't covered any design details or much of the process of getting your code into a microcontroller. This will happen in our next article when we'll create our first flowchart, debug it and show you how to upload the code to hardware.

We'll create a nice simple beginner's project with a step-by-step guide to creating a microcontroller-driven LED traffic light.

In the meantime, for more information please visit: <https://flowcode.co.uk/download> where you will find numerous guides. In particular, the *Embedded Guide* and *Arduino Guide* are recommended for beginners.

Try it for free

We hope you've found this introduction interesting, and if you'd like to try Flowcode for free then just go to <https://flowcode.co.uk/download/> and download the code. You'll get a 30-day free trial of the full version – but that's not all. Even after the 30 days are up your copy of Flowcode will continue to work, but at a reduced level with a limit on the size of program you can run and access to a more basic set of parts. However, for beginners it is still an ideal platform with which you can build and run programs, on for example, an Arduino Uno or a PIC 16F88.

Only when you are really sure that you want to use Flowcode do you need buy inexpensive access to say a Raspberry Pi or Bluetooth module (see: <https://flowcode.co.uk/buy/process/> for all the modules available and what they contain). What's more, as soon as you buy *any* module, the restrictions on the size of your code are removed.

PE discount!

One more thing, Flowcode is deliberately designed to be inexpensive, but *PE* readers can get a further 20% discount when they use the code **PE20** at checkout.

Martin Whitlock is Applications Engineer at Matrix TSL – the company behind Flowcode.



Fig.5. The 'Hello World' program running on a Sparkfun RedBoard.

PIC n' Mix

Mike Hibbett's column for PIC project enlightenment and related topics

Part 7: PIC18F Development Board

This month, we expand on the voltage monitoring capability we developed previously by logging the data to a file on a standard Micro-SD card, so we can download the data later to a PC. As our development board is already equipped with the necessary hardware, this month is going to be a software discussion. Bringing file storage capability into a small, embedded microprocessor project is a big task, even with the support of the Microchip Code Composer utility, so it's worth taking some time over this.

The hardware interface, shown in Fig.1, is very simple electronically – it's just regular SPI (Serial Peripheral Interface). There are additional functions available on card sockets, such as a pin that signals when a card is inserted and a write-protect signal, but for an application such as ours, where the card will always be connected and inside an enclosure, it is perfectly acceptable and common to ignore those extras and stick with standard four-wire SPI.

To make life even more interesting we are going to add one further feature into the mix this month – including a time stamp with the sample data as it is written to a file on the card. For data logging applications this is an essential feature, because knowing when a change in a sensed value occurs is often just as important as knowing what that sensed value is.

Tracking time

There are several relatively cheap ICs available that are specifically designed

to store and maintain a clock, with communication over I²C or SPI. These ICs are designed to operate with a small battery which will keep the clock running when the system power is turned off. Your PC, laptop and mobile phone have one of these devices (in PCs and laptops, the battery is typically a replaceable coin cell.) If you are happy to set the time and date when the system is powered on each time (we are, in this project) then that cost can be avoided as we have everything required in our existing hardware.

The processor contains a number of timer peripherals which can be configured to increment on every clock cycle (or on a division of the input clock signal) and generate an interrupt when a particular count (say, one second's worth of clocks) is reached. That interrupt could call an interrupt routine that updates a clock timekeeping variable by 1s. The timer peripheral can be configured to automatically restart; counting up from zero and giving you an accurate clock that is updated automatically without interfering with your main application.

For a clock to be useful, it must be reasonably accurate. Our processor operates on a clock signal generated internally, based on a resistor and capacitor to provide the reference frequency. This clock signal is calibrated during IC manufacture to 2% accuracy. That's perfectly fine for running code and communicating with other devices over serial interfaces, but it would be terrible for maintaining a real-time clock – it could lose 30 minutes each day. This is why we have a crystal fitted to our board, which oscillates accurately at 32.768kHz (but hereafter referred to as the '32kHz' crystal). The crystal is wired to two pins that connect internally to the secondary oscillator peripheral. This is designed to work with 32kHz crystals, a type of crystal that can run with very low power consumption. It's also such a low frequency that we can configure a timer to interrupt once every second, which will make our interrupt function nice and simple.

What's the date?

So, we now know how we will produce an accurate, one-second timer. Next we need to decide the format we will use to store the timestamp. A naive choice would be in a 'human-understandable format', for example: 02/07/2021 11:25.

That format is easy to read by both humans and computers but has several problems. First, is that date in Day/Month or Month/Day format? Is the time in 12-hour or 24-hour format? If 12-hour format, what is the pm indicator going to be?

You can define these settings in advance of course, but it is not trivial to update this information in software – you need to allow differing number of days in each month, and for leap years. These problems, however, are nothing compared to the main issue. What time zone is the device operating in? Also, daylight saving time, when the clock moves forward or backward by an hour, depends on your particular time zone. Or rather, the time zone your device runs in. This can quickly become extremely complicated to manage, for what should be a relatively simple problem.

Thankfully, this problem has been considered before, and a simple solution proposed – 'Unix Time'. This is a simple 32-bit positive integer, which marks the number of seconds since 1 January 1970, UTC. By storing and maintaining a Unix Time variable, we only need to increment it by one every second, using the very simple algorithm we discussed earlier. The interpretation of what that value means can then be left to whatever application the user is using to display or process the data. This means, instead of

PIC n' Mix PIC18F Development Board

The PCB for the *PIC18F Development Board* is available from the *PE PCB Service* – see the July 2021 section.

www.electronpublishing.com/product-category/pe-pcb-service/

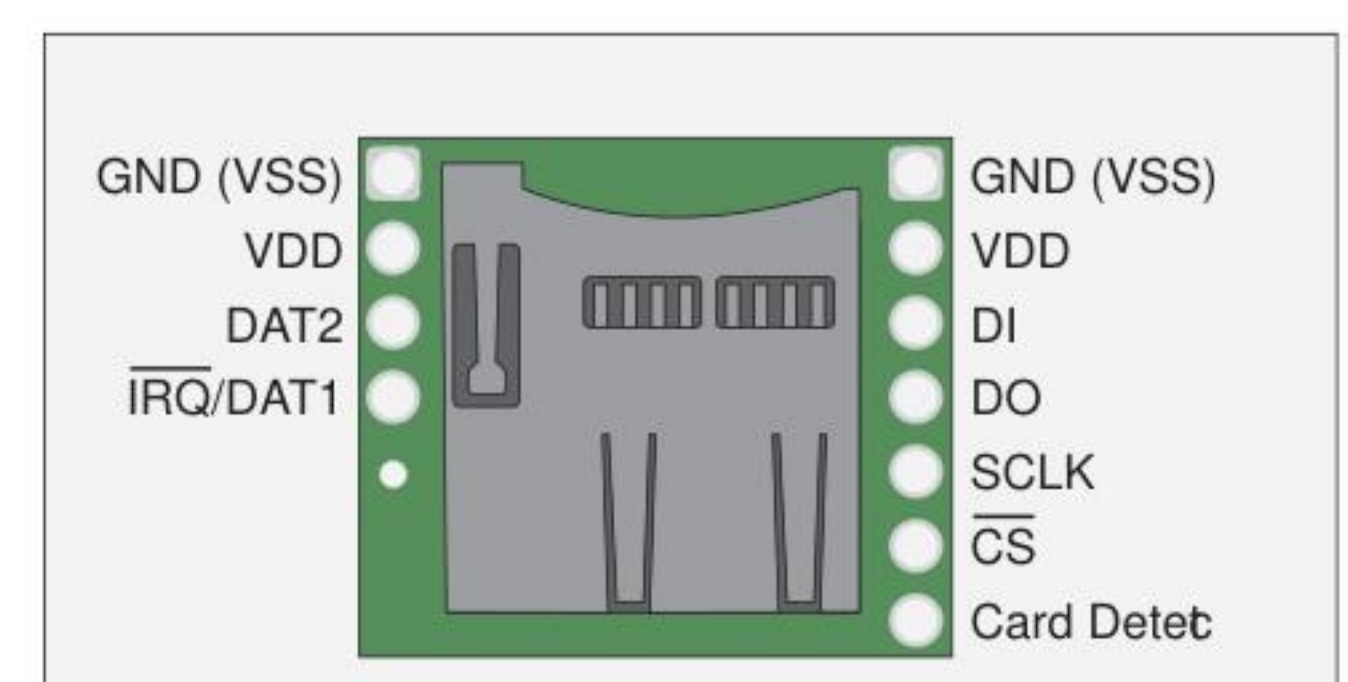


Fig.1. Micro-SD card connector pinout.

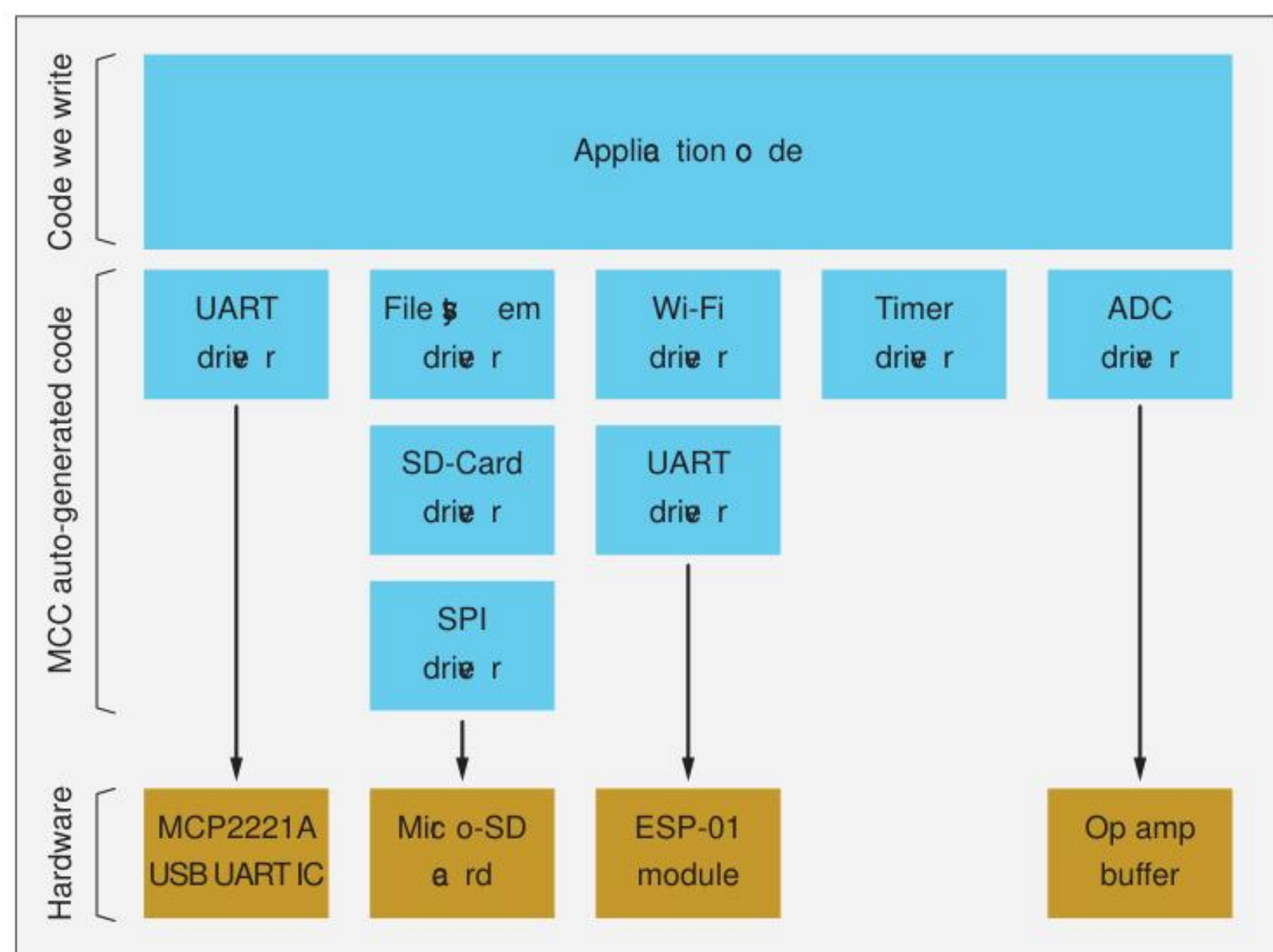


Fig.2. Software architecture, showing how the program is made up in layers. Thanks to MCC, we only need to write one layer of software.

writing '25/06/2021 18:25' to a data file, we would write '1624641898'.

Essentially, we push the problem to the system displaying the datafile content, and there is a very good chance that system would be a PC, connected to the Internet, and able to make sense of the time zone it inhabits, and adjust the data it is receiving as appropriate to the time zone settings the user has specified.

This makes our life much easier. If you would like to convert a value from Unix Time to local time, there are online tools to help, for example: www.unixtimestamp.com

In summary, we will store a timestamp for each data sample recorded, using Unix Time. Initially, when our device starts up we will set this time to 0, but in the next article we will provide an interface for setting the true current time value.

Software architecture

As we move forward with the software for this application, we start to move away from a simple design to something with quite a complex organisation. This is a good time to talk about how we segregate program functions in a way that simplifies the design of the overall system: by breaking the design down into smaller chunks. We do this using two concepts: software drivers, and software layering.

A software driver is a piece of software that performs a specific job. It is typically a set of variables and functions that provide some kind of service. One example is a serial port driver. This contains the code to configure the UART port and provides a character transmit and character receive function. The application can then call these functions to send data over the UART port without requiring the application code to 'know' that a UART is being used. When properly written, the driver code could be removed and replaced with another driver

creates drivers for us, so it makes sense to draw out a design for our project based on this approach, as shown in Fig.2.

The simplest driver shown here is the Timer. The driver code contains all the configuration settings and functions to interact with the timer and gives us two very simple functions to use – one to start the timer running, and one to handle the periodic interrupt. Neither of these functions require us to look at the datasheet of the processor to understand how to use them.

A more complex example is how we access files on the Micro-SD card. The file system driver will provide functions such as 'open file', 'write to file' and 'read from file'. The file system driver knows nothing about how those files are stored on the card; it uses the SD-Card driver to manage that. Likewise, the SD-Card driver does not know how to communicate with the card via the physical interface; it uses an SPI driver to do that for us.

There are several benefits to this approach. First, most of these (quite complicated) drivers are created for us by the MCC tool. Second, if we were to change, say, to a USB-based memory stick, the file system driver and our application code would not change – only the lower layer driver would need to be replaced.

By the time we finish our application this month you will see the benefits. The application code we write will be simple, and easy to read.

The most complex of the drivers we will be using is the file system driver, called 'FatFs'. This allows us to create, read and write to files in a format that can be read by a computer. FatFs is actually a third-party library, created and maintained as a hobby project by an engineer in Japan. It's been a freely available library for over 15 years and has been very professionally maintained by the owner over this time. With the latest updates made just a few

(perhaps to send data over a Bluetooth link) without the application code requiring any changes.

'Layering' is the technique of creating drivers at different degrees of abstraction from the underlying hardware. When we draw this as a diagram, layers that are closer to the hardware are at the bottom, with the level of abstraction increasing as we move up. The final application code appearing at the top.

The MCC tool cre-

months ago, it's clearly a popular, valuable and effective driver. Microchip have integrated it into the MCC tool which saves us having to 'integrate' it ourselves – so many thanks to both parties for making our lives easy! If you are interested in viewing the history of the development, you can find the author's website here: http://elm-chan.org/fsw/ff/00index_e.html

Adding the drivers

Before making any updates to our application code, we need to add the drivers into our project. We start by opening up the project files from the previous article. These can be found on the September 2021 page of the *PE* website in a single zip file (named **picnmix-sept-beginning.zip**). Unzip the file into a directory of your choice. The top-level directory within the zip file is: **monitor.X**

Now open MPLAB, click on 'Open Project...' and navigate to the directory containing the **monitor.X** directory you just created. You will see it shown with an IC icon next to it in the file listing, indicating that MPLAB recognises it as an MPLAB project. Double click on **monitor.X** to open the project.

Next, click on the MCC icon on the top menu bar, which should bring up the 'Project Resources' and 'Device Resources' windows on the left-hand side, as shown in Fig.3. The Project Resources window shows the features already included in our



Fig.3. MCC Resources windows.

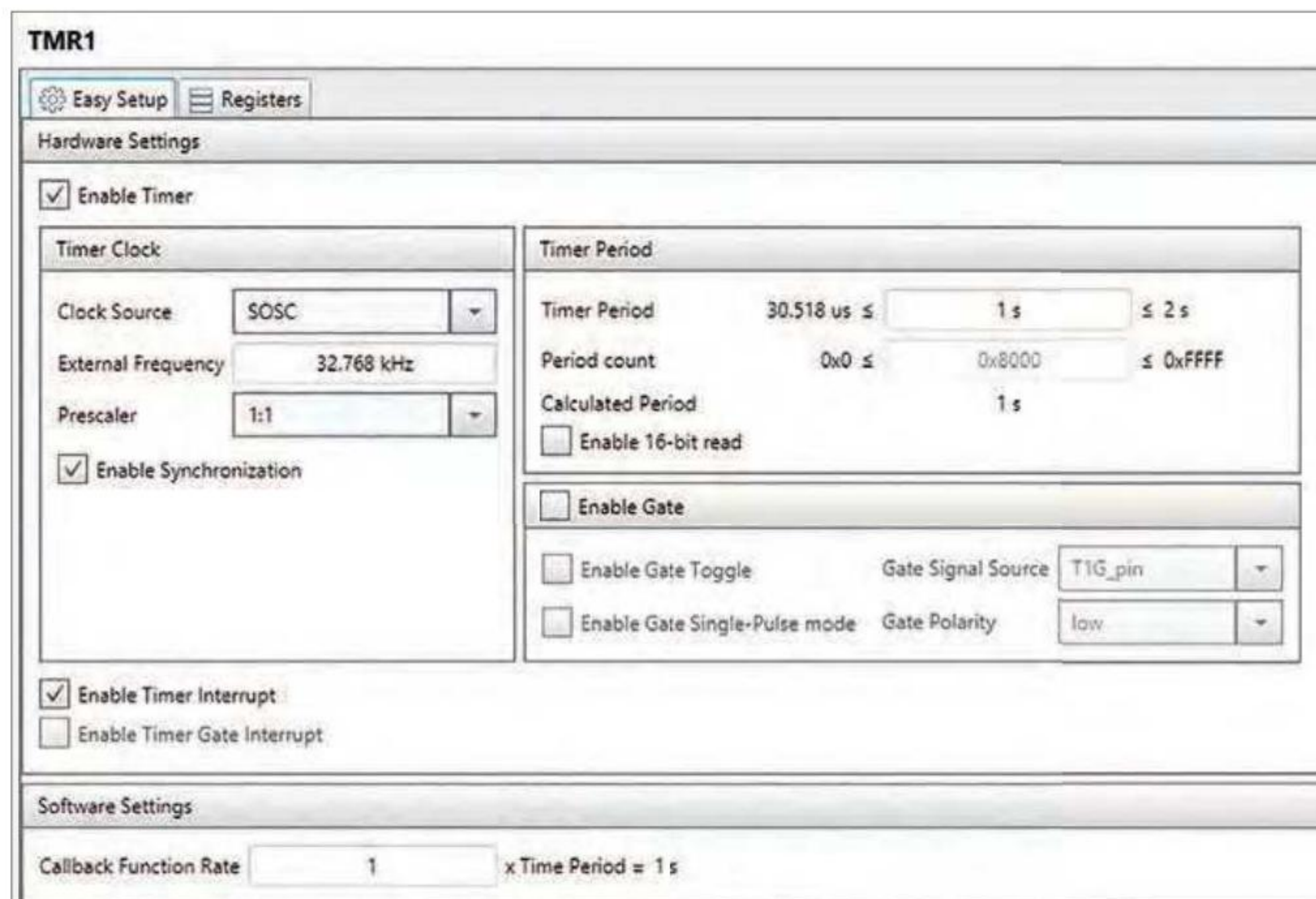


Fig.4. TMR1 configuration window.

project (we did that in the previous article), and Device Resources also lists those additional drivers available for us to add.

Let's start with the simplest driver – we want to add a timer, which we will use to maintain a 'Unix Time' clock. Scroll down the Device Resources list to the 'Timer' drop down entry, expand it (by clicking on the triangle icon) and click the '+' icon next to 'TMR1'. Change the 'Clock Source', 'Timer Period', 'Enable Timer Interrupt' and 'Callback Function Rate' as shown in Fig.4. These changes configure TMR1 to use the secondary oscillator inside the processor which is connected to the 32kHz crystal. Then click the 'Generate' button at the top of the Project Resources window. Notice that we have enabled interrupt operation – we have chosen to enable the timer interrupt to allow the timer to run in the background so that our main application does not need to handle looking for an actual timeout event once a second. We will instead use the 'callback function', which is a function we write that will be called by the timer code once every second in the interrupt handler. All of which is managed for us by MCC. Again, simplifying our interaction with the timer specifics.

The generation process creates a number of new files and adds these into our project directory. The interesting ones for us in this case are the two files **tmr1.c** and **tmr1.h**

tmr1.c holds the source code for the peripheral's configuration, which we do not need to look at. **tmr1.h** contains the 'API', the list of functions that we can make use of in our application. Looking through this file, we can find the important functions for us for this project.

The first interesting function is **TMR1_Initialize()**, which sets the

peripheral's control registers. This is important, but is called for us automatically by the **SYSTEM_Initialize()** function already present in our **main.c** file. That function was updated automatically when we clicked the Generate button.

Next up is **TMR1_StartTimer()** – we call that to start the timer running. We can do this at any time after the call to **SYSTEM_Initialize()**, so we copy it into our **main.c** directly after that line of code. While in **main.c** we have to uncomment this line:

```
//INTERRUPT_GlobalInterruptEnable();
```

Doing this allows the timer interrupts to be actioned by the processor.

Finally, back in **tmr1.h**, we find an important function: **TMR1_SetInterruptHandler()**

It is not immediately obvious, but this is the function we call to assign our timer callback function. Let's head back to **main.c** and implement that function. First, we need a global variable that will be our Unix Time counter. We create that just above the **main()** function. Then we write a simple callback function – this just increments that Unix Time variable by one each time it is called. The code looks like this:

```
uint32_t unixtime = 0;

void timer1_callback(void)
{
    unixtime = unixtime + 1;
}
```

Note, the name of the function can be whatever you want.

Finally, **TMR1_SetInterruptHandler()** is the function used to assign our callback function to the timer driver. To do this we

add the following line of code just before the **TMR1_StartTimer()** call:

```
TMR1_SetInterruptHandler(timer1_callback);
```

That's it – if we run the code in debug mode on our development board, we should see the Unix Time counter incrementing when we pause the program.

Now we get to the slightly more challenging part, adding support for the Micro-SD card.

We start by adding the 'SD Card (SPI)' driver from the Libraries section of the Device Resources window. This automatically brings in the SPI1 driver at the same time. Next, add in the FatFs driver. Now, we are ready to configure these drivers. We will start at the lowest layer, the SPI1 driver.

Click on the SPI1 driver in the Project Resources window; then, in the SPI1 driver details window that appears, we change the 'Clock Divider' from 0 to 64. This reduces the SPI clock frequency down to 123kHz. Why? That's because Micro-SD cards must, on their initial configuration following power on, be run at a very slow speed, presumably for compatibility reasons. We can increase the speed of access later. Right now, it's not clear how we would do that within the software, so we will leave it as is and move on.

In the SD Card (SPI) driver window, uncheck 'Enable Card Detect (CD)' and 'Enable Write Protect (WP)', as these are features, we do not need in our application.

We must now make sure that the correct processor pins are assigned to our SPI interface. Open the 'Pin Module' from the Project Resources window by double-clicking on the name, and then select the 'Pin Manager: Grid View' in the lower window. Notice how some pins have already been allocated for the SPI1 module. Click on the padlock symbols to select the correct pins as defined by our circuit. Then, in the 'Pin Module' window, click 'Start High' for the SDCard_CS signal (it's an active low), and also unclick the 'Analog' checkbox associated with RC3. Your settings should look like Fig.5.

Now we can turn our attention to the file system driver. Click on the FatFs label in the Project Resources window, then in the FatFs window that appears, click on the 'Configuration' tab.

The list that appears is long, so we will concentrate only on the features that we will change from their defaults. We start by leaving the 'Generate example/demo files' checkbox set, as these files may serve as a useful reference later. Next, we must tell FatFs what SD-Card driver it should use to communicate with the physical card. You could – in theory – have several

This error is emitted by the compiler, so let's take a look at the offending lines of code:

```
if (FF_USE_STRFUNC == 2 && c ==
'\n') { /* LF -> CRLF conversion */
    putc_bfd(pb, '\r');
}
```

We can see that this block of code should never be called, since `FF_USE_STRFUNC` is set to 1, not 2. We were unable to find an answer on the Internet as to why this issue occurs, so we simply commented out the code. On re-building the project,

we end up with a successful build with a 30% utilisation of code and memory – that's perfectly fine, and plenty of space remaining to allow us to add extra features. This kind of issue probably arose because there are so many different configuration options for FatFs, we may have selected an unusual combination. No matter, the issue appears to have been easy to correct.

Before we test the code, we must prepare a Micro-SD card by formatting it on a PC. This does two things – it removes old files from the drive, freeing up space (make sure you take a copy of any valuable files first!) and it also allows you to specify the type of file system that will

be on the disk. There are typically three options to choose from – FAT32, NTFS or exFAT. Ensure you select FAT32 – the other two are not supported with the configuration of FatFs that we are using. The file system is a specification for how files are stored on the card, and how a program accessing the card can locate those files. Different file systems have different benefits, but for use with an embedded system design, FAT32 is perfectly acceptable – you will be hard pressed to find any limitations (for example, file sizes are 'limited' to a maximum of 4GB.)

Eject the card from your PC and insert it into the development board socket. Start the code running, allow it to continue for a few minutes, then stop the code, remove the card and re-insert it into your PC card reader. You should find the file **a.txt**, which when opened with a text editor such as notepad, should reveal the written data.

Wrapping up

By integrating the wonderful FatFs library into MCC, Microchip have made bringing access to huge amounts of cheap persistent data storage a breeze. Micro-SD cards are not only great for storing data, but also for storing configuration information, readable data sets (like graphics or sound) and even firmware updates. The full source code for this month's article – both the starting point and the final functional code – is available for download from the September 2021 page of the *PE* website.

We have now reached a stage where (in theory) the software is functional enough to perform the task we originally set out to do – monitor a solar-powered device's power supply rails. There are, however, some enhancements that will not only make the hardware easier to work with but will also allow us to demonstrate the next major piece of functionality available on our development board – Wi-Fi.

Coming up next

In our next article we will look to add in the Wi-Fi interface so we can read the data file from the device remotely. We'll also add some user interface features, implemented to be accessed over the serial interface. We will also use the Micro-SD card to store a text file containing our Wi-Fi credentials, rather than hard code them into the program. At that point we should be done and can move the circuit from the development board to a small circuit and put it to practical use.

PIC n' Mix files

The programming files discussed in this article are available for download from the *PE* website.

Listing 1: Our updated application code.

```
// Mount the SD Card, and do it immediately
fr = f_mount(&fs, "", 1);
// stop here if there was an issue mounting the drive
if (fr != FR_OK) {
    printf("*** Failed to mount disk\r\n");
    do {} while (1);
}

while (1)
{
    fr = f_open(&fil, "a.txt", FA_OPEN_APPEND | FA_READ | FA_WRITE);
    if (fr != FR_OK) {
        printf("*** Retrying file open\r\n");
        fr = f_open(&fil, "a.txt", FA_OPEN_APPEND | FA_READ | FA_WRITE);
        if (fr != FR_OK) {
            printf("*** Failed to open file\r\n");
            do {} while (1);
        }
    }

    ADCC_StartConversion(channel_ANA0);
    while(!ADCC_IsConversionDone());
    solarPanel_volts_adc = ADCC_GetConversionResult();
    solarPanel_volts = (double)solarPanel_volts_adc;
    // Convert ADC value to volts, compensate for divide by 2
    solarPanel_volts = (solarPanel_volts * 3.3 * 2.0) / 4095.0;

    ADCC_StartConversion(channel_ANA5);
    while(!ADCC_IsConversionDone());
    battery_volts_adc = ADCC_GetConversionResult();
    battery_volts = (double)battery_volts_adc;
    // Convert ADC value to volts, compensate for divide by 2
    battery_volts = (battery_volts * 3.3 * 2.0) / 4095.0;

    // Print the values over the serial port
    sprintf(str, "Time: %ld: Battery voltage: %1.2f, Solar voltage:
    %1.2f\r\n", unixtime, battery_volts, solarPanel_volts);
    printf(str);
    bytes_written = f_puts(str, &fil);
    if ((bytes_written < 45) || (bytes_written > 99)) {
        printf("*** Failed to write to file correct number of bytes.\r\n");
        do {} while (1);
    }
    __delay_ms(500);
    f_close(&fil);
    __delay_ms(500);
}
```


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Vigortronix 600Ω VTX-101-3001 £10
Gardners 150Ω £10
Reclaimed BBC LL74/MPC nickel core 600Ω £12

Reclaimed mic input transformer £15

Inductors

82µH, 4.7mH, Theremin 100µH, 270µH £2.00
7-inch ferrite rod with MW and LW windings £3.00

Special resistors

Bourns wire-wound trimmer 5kΩ
3059 JM panel-mount £2.00
Thermistor RA53 £4.00
Thermistor CZ1 £1.50
Holco H2 2.2MΩ 1W £1.00
Welwyn 1GΩ 2W £1.00
Allen Bradley 1.2kΩ 2W C-comp £1.00
Lots of big valve resistors available.

Potentiometers

Bourns 81

25kΩ lin cermet £2.00
25kΩ lin conductive plastic £3.00

Plessey moulded-track

5kΩ log with switch £3.00
50kΩ A/log £3.00
Mil 250kΩ lin dual £5.00

Alpha

16mm 4.7kΩ A/log £0.80
220kΩ A/log £0.80
10kΩ lin centre-detent dual-gang £1.50

Allen Bradley J series/Honeywell

10kΩ lin 1 million cycles £5.00
Blore Edwards AB 45 dual 5kΩ A/log with switch £3.50
Alps RK9 dual-gang 5kΩ RD law £4.00
BI P260 500kΩ log conductive plastic 1 million cycles £3.00
Colvern wire-wound 100kΩ or 50kΩ dual-gang 3W £8.00
Mil Spec hermetic 10Ω £8.00

Miscellaneous

Theremin Clearance Sale!

Elysian Theremin MIDI box £300

PCBs

Pocket Theremin £4.00
Elysian Theremin £12
Synth VCF, VCO £3.00
48V PSU £3.00

Relays

STC hermetic 4190 24V DPDT £4.00

Switches Blore Edwards/Plessey

MH1 4-pole 3-way £3.00
Elma 01 2-pole 6-way £6.00
3PDT guitar pedal stomp switch £2.50

Valves

EC88, PCL84 £3.00

Robert's Radio modules

Tuners LP1169, LP1179 £7.00
IF strip LP1171 £7.00

Knobs – large Bakelite

Bulgin 1960s and Sifam 1970s £1.50

Contact

Jake Rothman
The Old Rectory, Arlais Road,
Llandrindod Wells, Powys
LD1 5HE (visit by appointment)
+44 (0)1597 829102
jrothman1962@gmail.com

Minimum order £5.00 inc post
Quantity discounts negotiable

Payment

PayPal, cards (via phone), bank transfer, cheques (UK pounds only)
No VAT payable

Postage

Small Jiffy bag £2.99
Small package £4.99
Big boxes and overseas at cost – ask for a quote

Dissecting devices – a photographic feast



Fig.1. AF118 transistor internals from a Leak Stereo 30 amplifier – the central rectangle is the mounting assembly for the germanium transistor (6×4mm).



Fig.2. View looking into the can cut off from the AF118 in Fig.1. Tin whiskers can be seen growing from the lower left-hand inner edge (see also Fig.3). The white filling is a mixture of silicone grease and aluminium oxide to conduct heat away from the junction.*

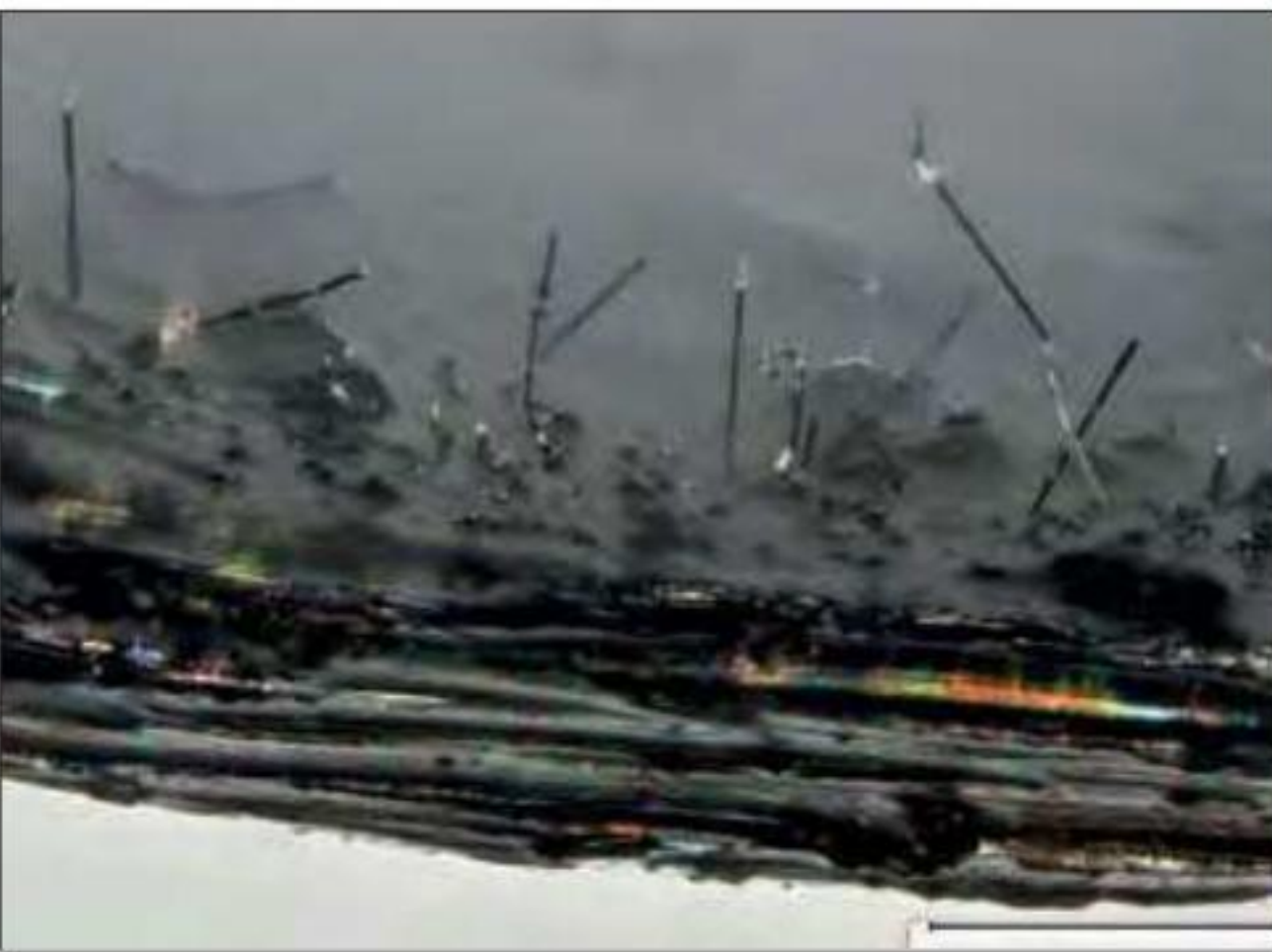


Fig.3. A close-up of the whiskers in Fig.3. The long one is 2mm.*

This month, the *Practically Speaking* column is a little different – it is still very much about the practical side of electronics, but I’m going to concentrate on a frequently overlooked side to electronic construction and repair work – using your eyes.

Back in 1971, aged nine and living in Fallowfield, Manchester, there was some waste ground where we used to play. Next to it was a wall, over which the local TV shop used to throw unwanted electronics! We enjoyed smashing valves, imploding cathode-ray tubes and bashing magnets off speakers with bricks. We were happy little vandals. Eventually, though, I developed more methodical disassembly methods. I learnt a lot about how electronic equipment and components were made, which in turn helped with physics at school. I still love taking things to bits – just like Dave Jones, who on his great Australian blog (www.eevblog.com) says, ‘Don’t turn it on, take it apart’. Here I’ll show how looking inside components can reveal interesting operations, constructions and failure modes, as well as being a great electronics education.

Tin whiskers

Following on from my last few *Practically Speaking* columns, where I restored a Leak Stereo 30 amplifier, I mentioned about the failure of germanium AF11X series transistors due to tin whiskers growing from the case inside. I like to see things in physical form for myself, so I decided to get out the hacksaw and cut open the failed AF118, shown in Fig.1. Dr Joe Botting, a palaeontologist next door, has a high-resolution microscope and he took some fascinating photographs of the de-canned device. The transistor was indeed riddled with tin whiskers, as shown in Fig.2 and Fig.3. Fig.4 shows the result of using an electron microscope on an AF114 from NASA’s website.

Fig.5 shows an AF117, commonly used in British and European radios from the 1960s. The individual device shown here was a later, more reliable version. The semiconductor junction had been specially protected with clear epoxy resin and the plating changed to tin-plus-lead,

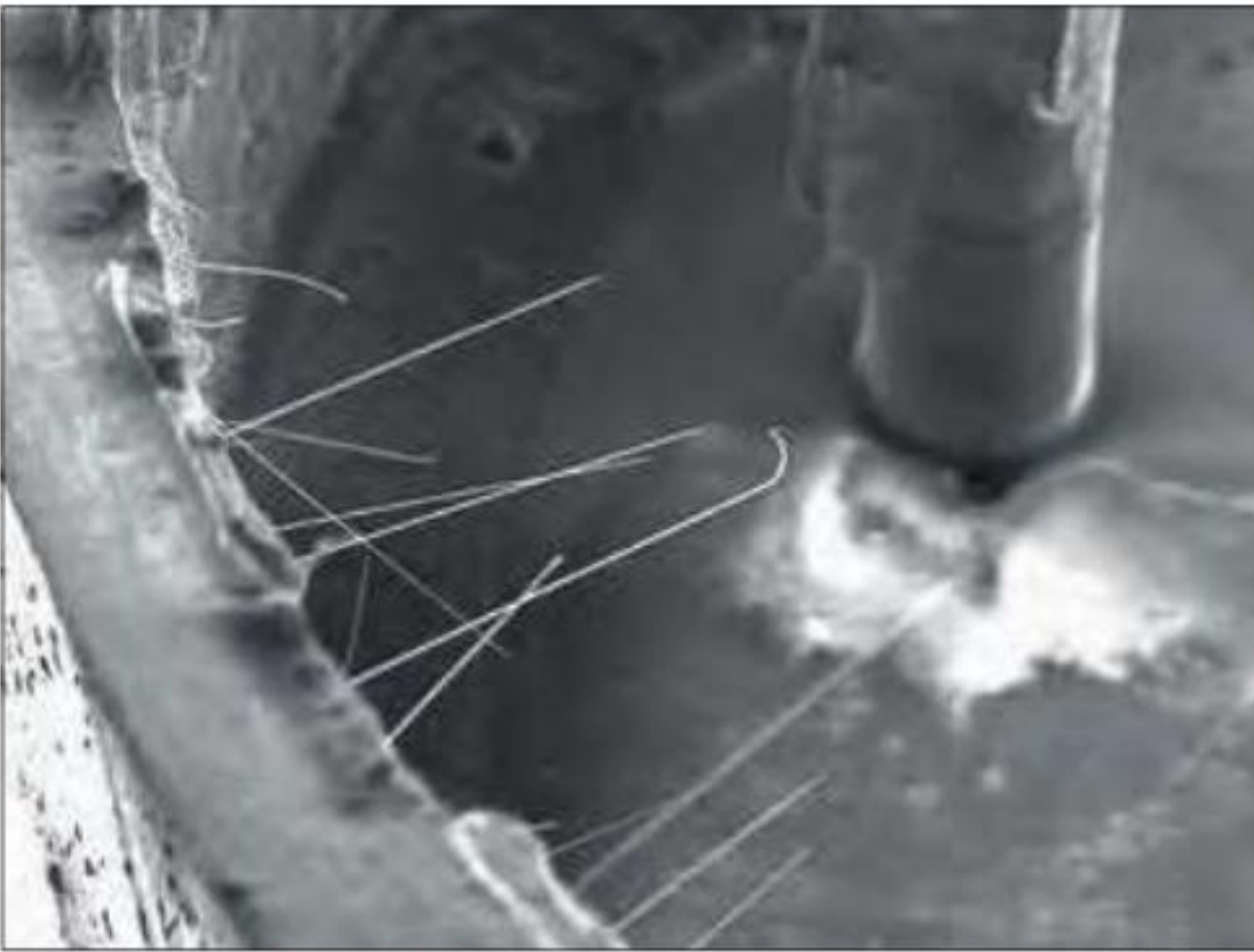


Fig.4. A NASA electron micrograph of tin whiskers in an AF114. Image credit: <https://go.nasa.gov/3wRXpwg>



Fig.5. The internal structure of an AF117 transistor – the assembly is mechanically protected with clear epoxy resin.*



Fig.6. ‘Unlimited’ currents can even burn through the steel case of a MOSFET.

inhibiting whisker growth. Eventually, the manufacturers changed the packaging to the familiar TO18, such as the AF124.



Fig.7. To open metal-can devices cut around with a hack saw. Don't cut in too far to avoid damaging the bonding wires.



Fig.8. Squeezing the metal tab of a plastic power device in a vice can remove the top epoxy revealing the die bonding site, and allowing its size to be measured.



Fig.9. Usually, the chip is cracked apart using the vice technique, but with some transistors, such as this Sanken device, there is a resilient compound applied above the chip allowing a clean view. Here the multi-fingered emitter of a good quality device is revealed.

Visual inspection

Until recently, electronics was a very visual skill and a simple visual inspection of components could reveal a lot. Fig.6 shows a MOSFET from a Lee Lighting controller used in film production. It had latched hard-on, passing a few hundred amps thanks to a brass spacer that had (very foolishly) been inserted in the fuse socket. Here, the thermal damage is pretty obvious, but often a device has to be cut open to reveal the fault. With metal-cased



Fig.10. A Motorola MJ2955 (PNP complement of the 2N3055). This device has suffered excess current due to shorting. Note the fused emitter bonding wire towards the top.

devices, a hacksaw and vice work well, as shown in Fig.7. Plastic-cased devices are less yielding of their internal secrets and have to be squeezed 'till t'top pops off', as illustrated in Fig.8. A hammer and chisel can also work. Fig.9 shows a plastic power transistor where the chip is still intact. The serious under-the-bonnet silicon detectives over at zeptobars.com boil devices in concentrated nitric acid, sulphuric acid and oleum (disulphuric acid) – see:

<https://bit.ly/pe-sep21-inside1>

<https://bit.ly/pe-sep21-inside2>

Do not attempt anything with acid unless you really know what you're doing – it's dangerous, seriously dangerous. Even if you just want to crack open a device in a vice then eye protection is needed, since sharp bits can ping off suddenly.

Up the Junction

Opening up power transistors can sometimes reveal the destruction of junctions, such as Fig.10, which shows a blown 2N2955 transistor from a NAD 3020 amplifier.

Can opener

Old TO18, TO5 and TO99 cans are easily opened by carefully cutting around the edge with a hacksaw or Dremel power-tool. Fig.11 shows the audio engineer's favourite op amp, the NE5534 in a metal-can package.

It's worth remembering that cutting the tops off devices is not always pure destruction – topless old BC108 transistors make useful phototransistors.

Mystery Chips

I recently bought a box of mystery chips for a very low price (basically the gold scrap value) because no one could identify them (Fig.12). Now I'm pretty face-blind, but like many engineers I don't forget an interesting line pattern or number. When I photographed the mystery chip, I felt I had seen the mask

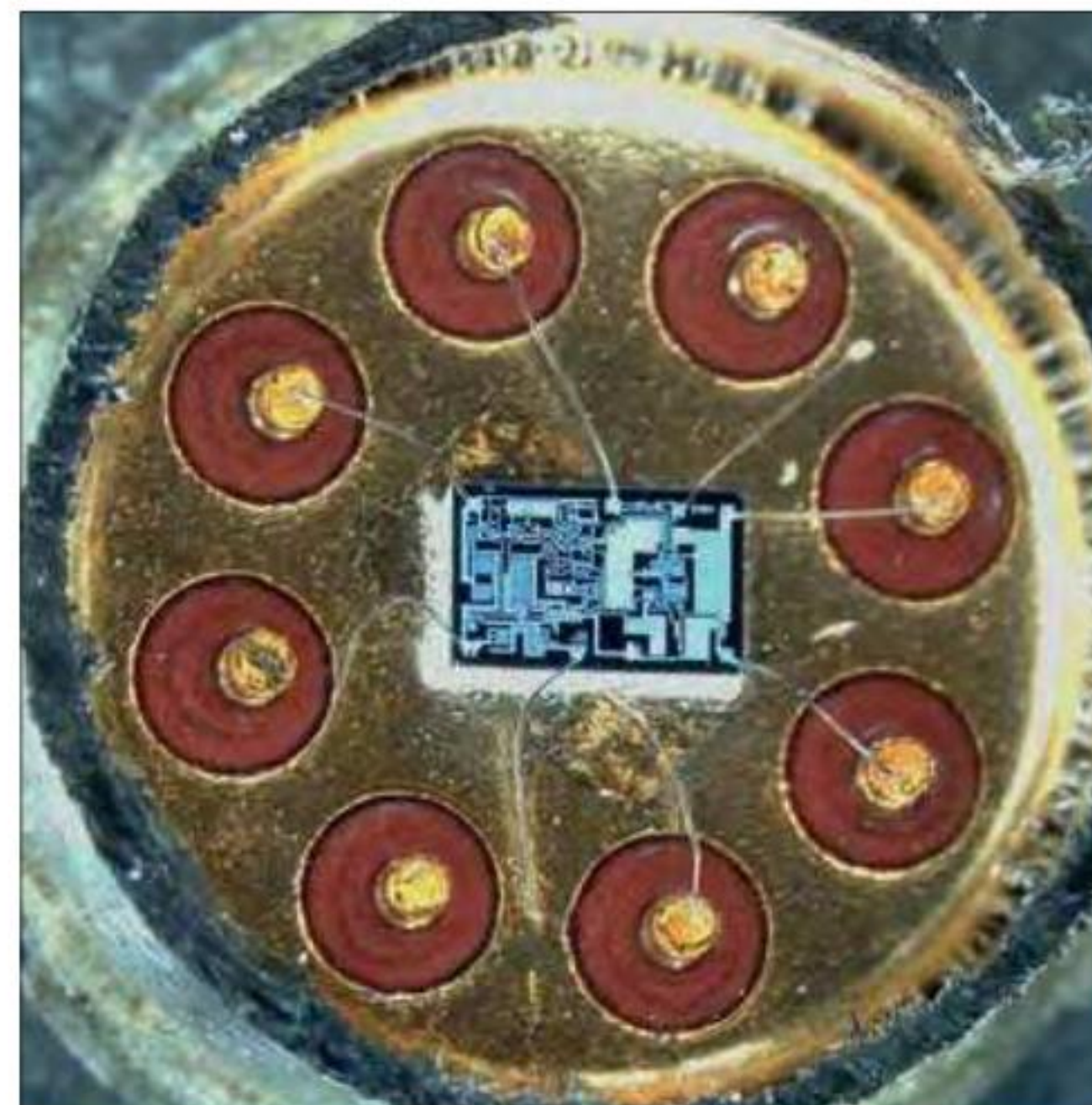


Fig.11. Top taken off a metal-can NE5534, the ever-popular audio op amp. *



Fig.12. Mystery box of chips. What is a U5B YY0939X. It was not until I identified it that I realised that the 'Y's were an Italian way of writing '7'.

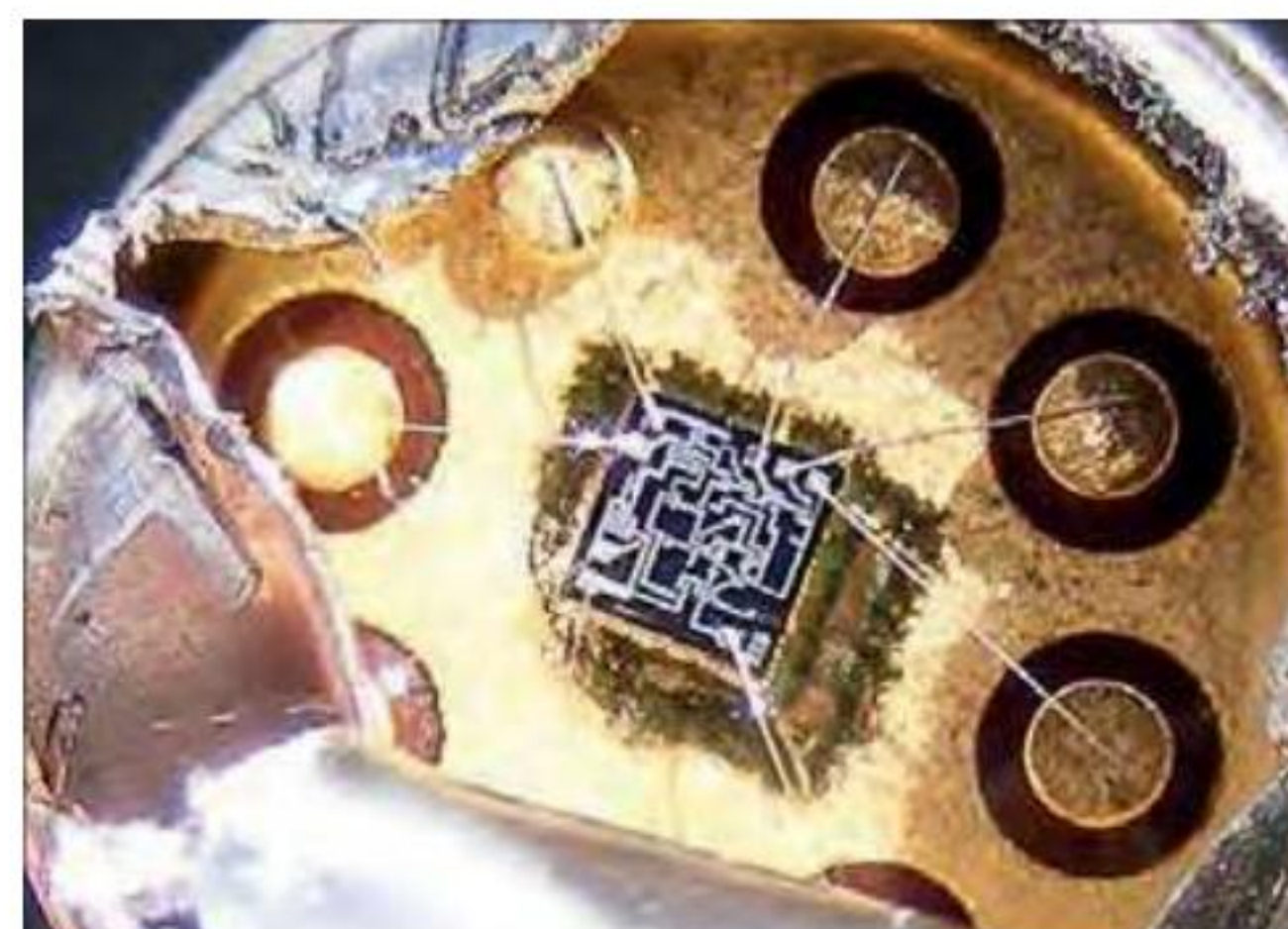


Fig.13. Internal die shot of the mystery chip from the parcel in Fig.12.

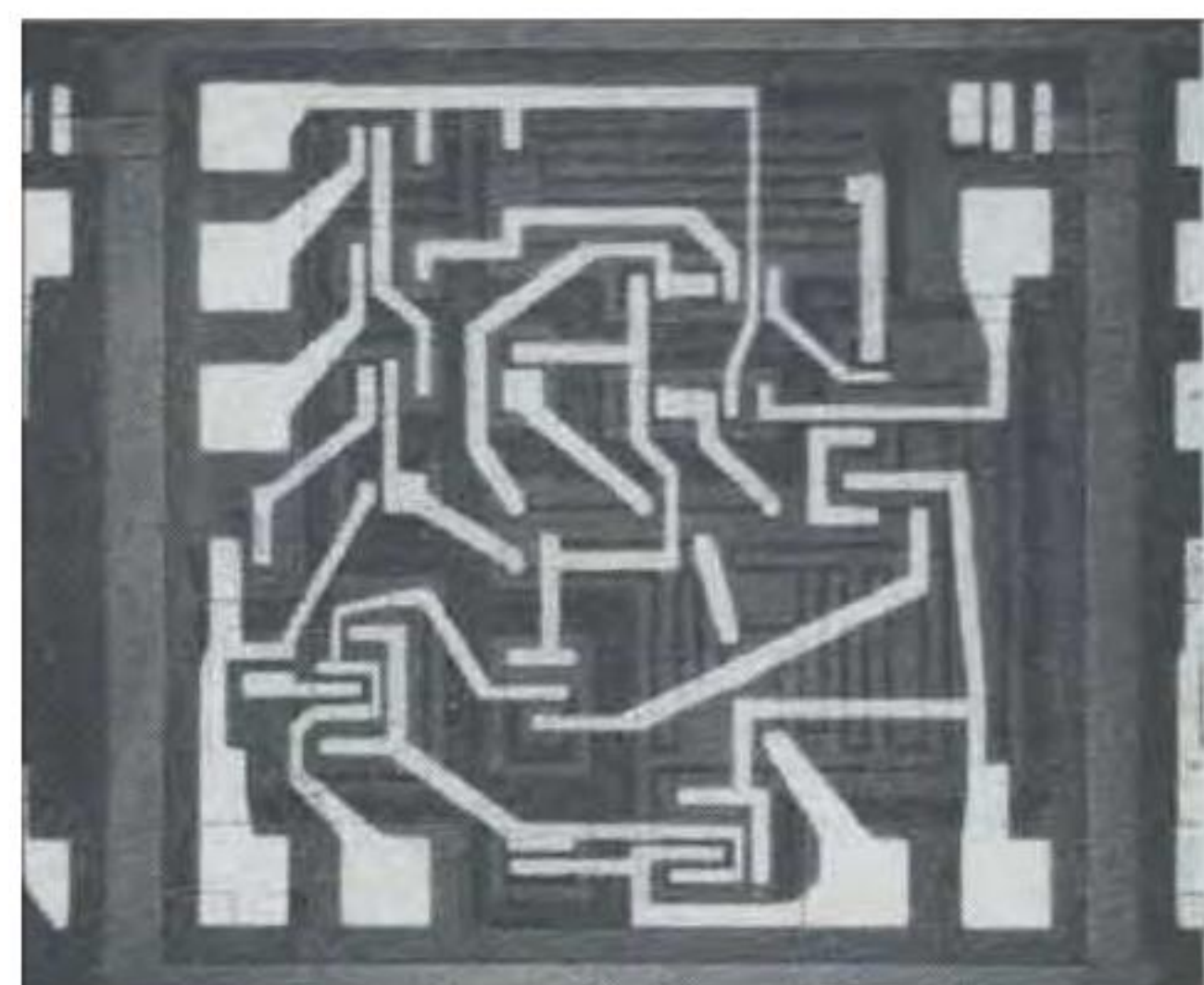


Fig.14. Notice the similarity? Page 119 of the March 1966 issue of *Wireless World* revealed that my mystery devices were just old μ A709 op amps; sadly no good for audio these days thanks to their horrid crossover distortion. Maybe Bletchley Park computer museum would like them?

pattern (Fig.13) before. I was sure I remembered something like it in an old *Wireless World* magazine which I had been reading while researching the Leak Stereo 30. I went back and there it was! in the 1966 issue shown in Fig.14. Despite the cryptic in-house code number which couldn't be Googled, it was just a boring μ A709 op amp. I've now got 140,

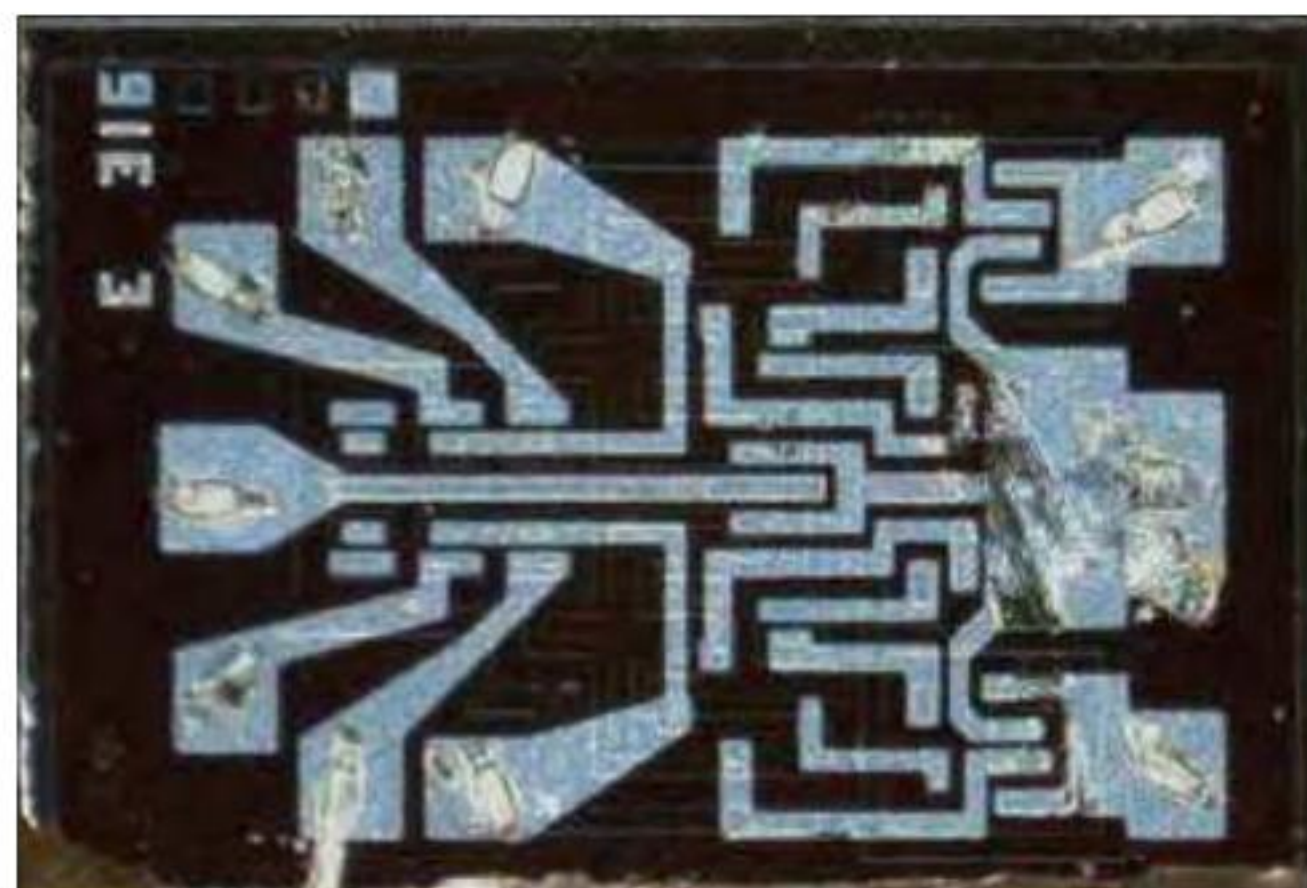


Fig.15. Plessey chip mystery – still unsolved.* It must be a special. Can anyone identify it?

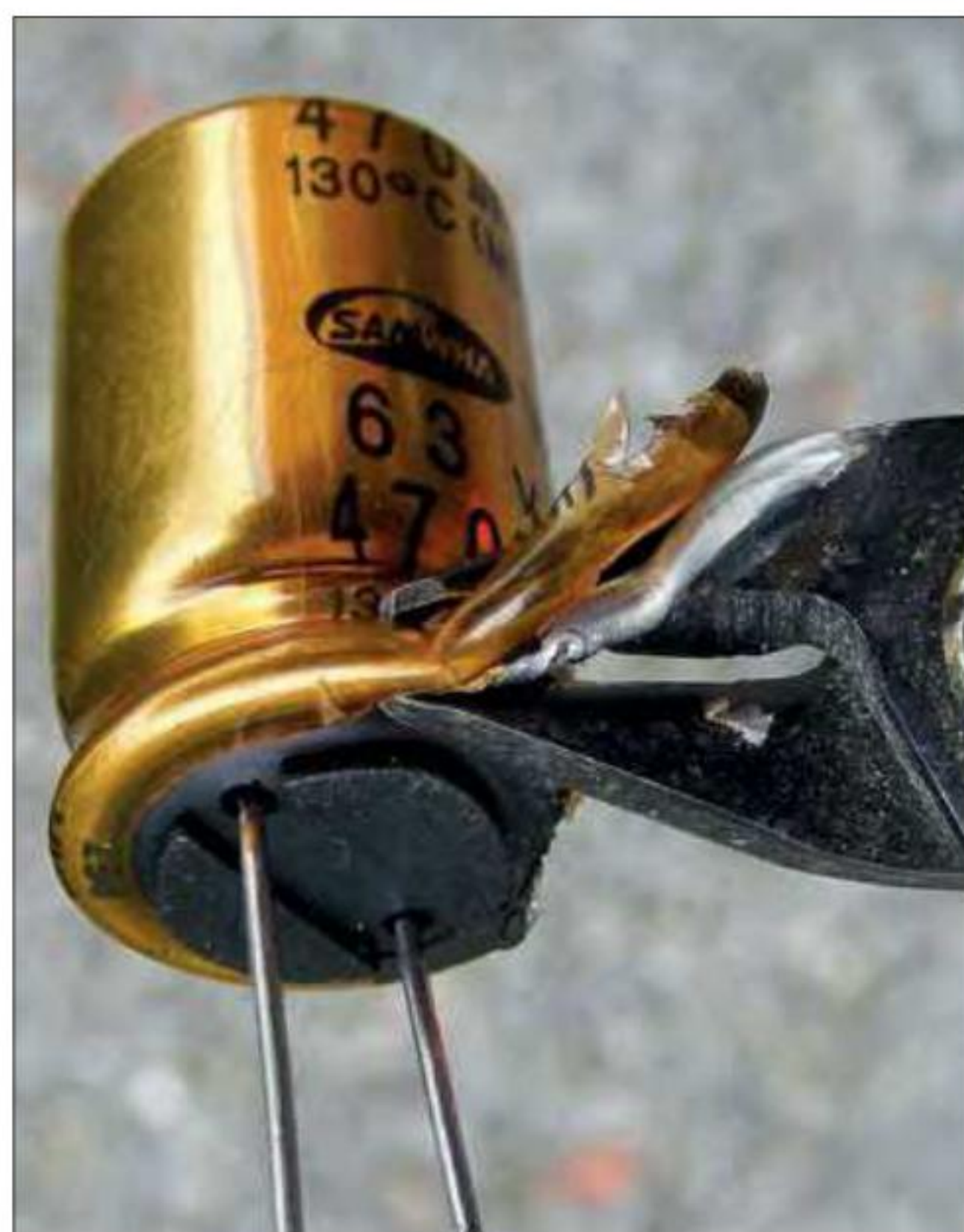


Fig.16. To open up an electrolytic, start cutting around the edge of the rubber seal. These were quite expensive Samwha devices rated at 130°C which suffered distended tops.



Fig.17. Once you have something to get hold of, then the rest of the can be 'unwound'.

for the *AO Shop* (see page 52 in August 2021 *PE*). I've also got a mystery Plessey chip shown in Fig.15. Any ideas?

Spam can

Electrolytic capacitors suffer all sorts of problems that are often revealed when disassembled. Opening them up requires a special technique with side cutters, illustrated in Fig.16. The capacitors shown were suffering hydrogen gas build-up in the case, causing swelling. This often happens with low-ESR types when they are not used frequently enough. In this case, there was a definite hiss as the rubber bung seal was broken. There was also a bit of spray. (Safety note: Use eye protection and wash hands, since the high temp ($\geq 125^\circ\text{C}$) types can contain DMF (di-methyl formamide) a potentially carcinogenic solvent and wet tantalum types use weak sulphuric acid). Once there is a strip of the can to get hold off, long-nosed pliers can be used to wind it back (Fig.17) like old cans of Spam.

Now the contents of the capacitor can then be pulled out by the leads. Fig.18 shows the foil/paper winding which has a healthy impregnation of electrolyte. Unwinding the capacitor, shown in Fig.19, revealed no problems, so the cause of the gassing remains a mystery, (possibly too much water in the electrolyte?). Needless to say, I put that capacitor stock in the bin. A piece of foil from another capacitor suffering internal pressure and electrolyte leakage is shown in Fig.20. Breakdown of the dielectric film has taken place.

Foiled again

Continuing our capacitor demolition frenzy, I'll attack an innocent polyester capacitor. I always get my first-year students to do this. I think if you can visualise the physical structure of a component, its function is more readily understood. Old fashioned axial film/

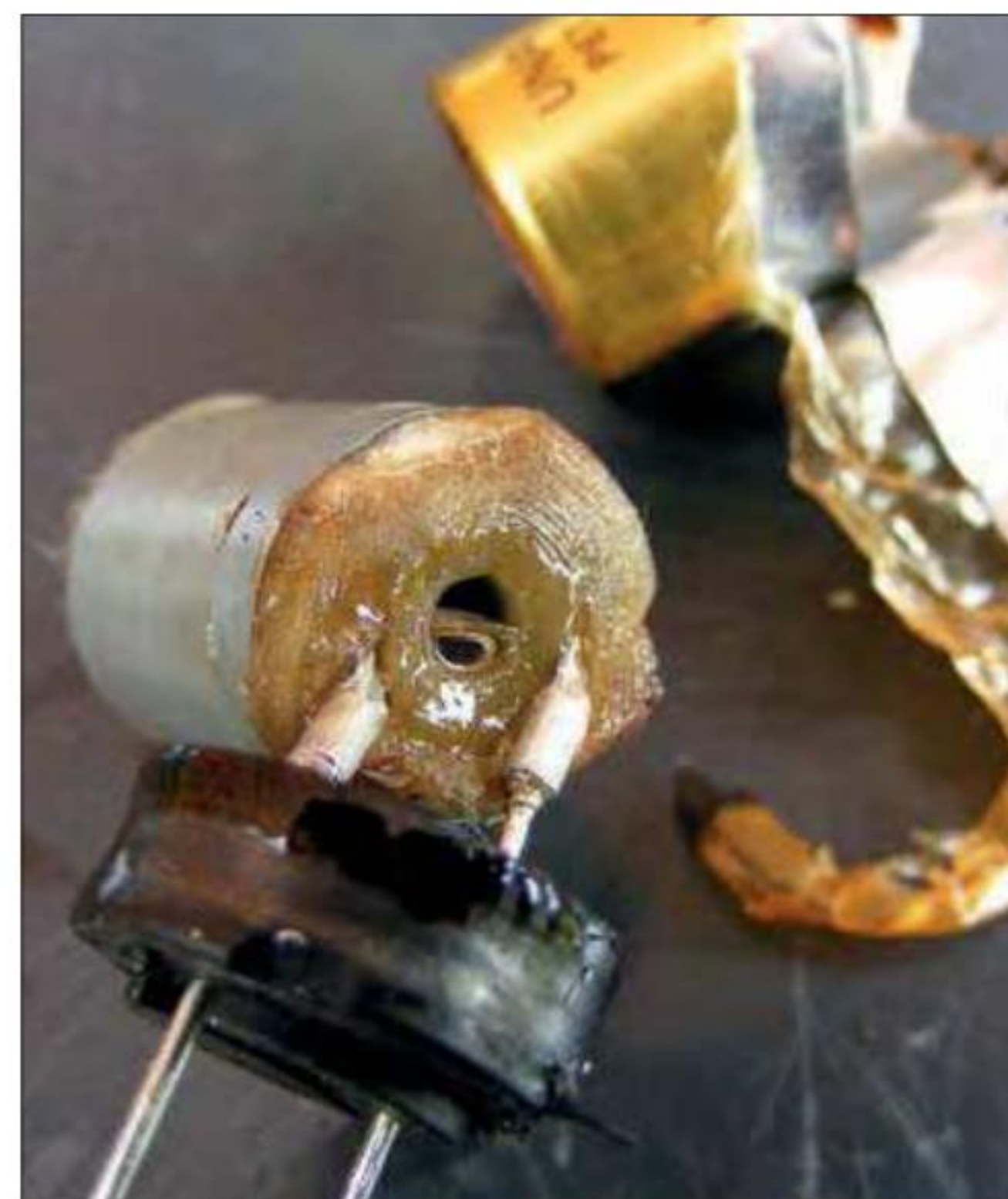


Fig.18. The wet guts revealed. The amount of electrolyte was healthy with no signs of being dried up. The composition of the electrolyte was suspect; maybe not enough corrosion inhibitors?



Fig.19. Unwinding the capacitor element (snip the tape holding it together first) shows the typical construction of an electrolytic capacitor: absorbent separator paper and grey etched anodised aluminium foil.

foil types, such as surplus SRC types are ideal. First, the capacitor has to be crushed with pliers to get the coating off, as shown in Fig.21. Then the capacitor



Fig.20. Foil from another expensive high-temperature electrolytic capacitor (Novea Secorel 125). Here, the oxide layer has decayed, some parts becoming almost bare metal. A shame because it had welded lead attachments, normally a sign of quality.



Fig.21. First stage in disassembling a polyester foil capacitor; crush the coating off with pliers.



Fig.22. Unwinding a polyester capacitor. Note the interleaved foils and plastic film.

can be unwound into its layers of plastic film and aluminium foil, as in Fig.22. This illustrates the massive surface area involved, even for a low-value capacitor. Fig.23 shows the effect of a pin hole in a metallised film capacitor. The metal burns away isolating the fault.

Tantalum devices

A problem with old silver-cased wet tantalum capacitors is shorts caused by silver deposits, as shown in Fig.24. These deposits can occur through very long storage times or reverse polarisation. Because of this problem, these capacitors have now been superseded by tantalum-cased types.

Opening up hermetic devices is often best done by applying a big soldering iron

to the case and melting the solder seal while pulling the glass sealed lead-out. This works well for metal-cased solid tantalum capacitors. It's one of the few times when those awful pistol-grip solder guns are useful in electronics. Often, the component can be fitted into the heating loop and the trigger squeezed. Fig.25 shows the slug from a 22µF 50V tantalum capacitor used in the microphone preamp. The 'spongy' texture of the sintered tantalum particles provides a massive surface area for the capacitor.

Inner secrets

Sometimes surprises lurk inside. I was disappointed to see that the expensive non-polarised tantalum capacitor in Fig.26 was just composed of two ordinary capacitors connected back-to-back.

Resistance is futile

Carbon-composition resistors are often described as being a solid block of resistive material giving very low inductance and high peak-power handling capability. I used a bench grinder to show this construction in Fig.27. Conversely, film resistors have high inductance and poor peak-voltage rating due to their thin coated spiralled track, but they do offer high stability and low noise. The best way to see the construction is to scrape off the coating, as shown in Fig.28. This is something I think all first-year electronic students should do.

Potentiometers

These are very easy to take apart by prising open the folded metal tabs on the front. Again, I make all my students do this because internally its function is visually obvious. I've always aimed to reduce abstraction to a minimum in electronics tuition. An inspection of the track on a faulty pot can be very revealing. The worn carbon track from the volume control of a Leak Stereo 30 amplifier is shown in Fig.29. No amount of Servisol contact cleaner spray is ever going to fix that – it has to be replaced.



Fig.24. A failure mode peculiar to silver-cased wet tantalum capacitors are silver growths, sometimes called 'Christmas trees' (the whitish blob on the left-hand side). These potential short circuits are caused by reverse polarisation or excessively long storage. Notice the oxide film on the tantalum slug has imparted a blue colour. This indicates the thickness of the film (for, in this case a 10V unit).



Fig.25. Sponge-like solid-tantalum slug. Here, the sintered slug is black because of the manganese dioxide solid electrolyte.*



Fig.23. In metallised film capacitors, self-healing of short circuits can take place. Here the metal has been vaporised from around a pinhole.



Fig.26. Disassembling a metal-cased non-polarised tantalum capacitor revealed it to be just two normal capacitors connected back-to-back.

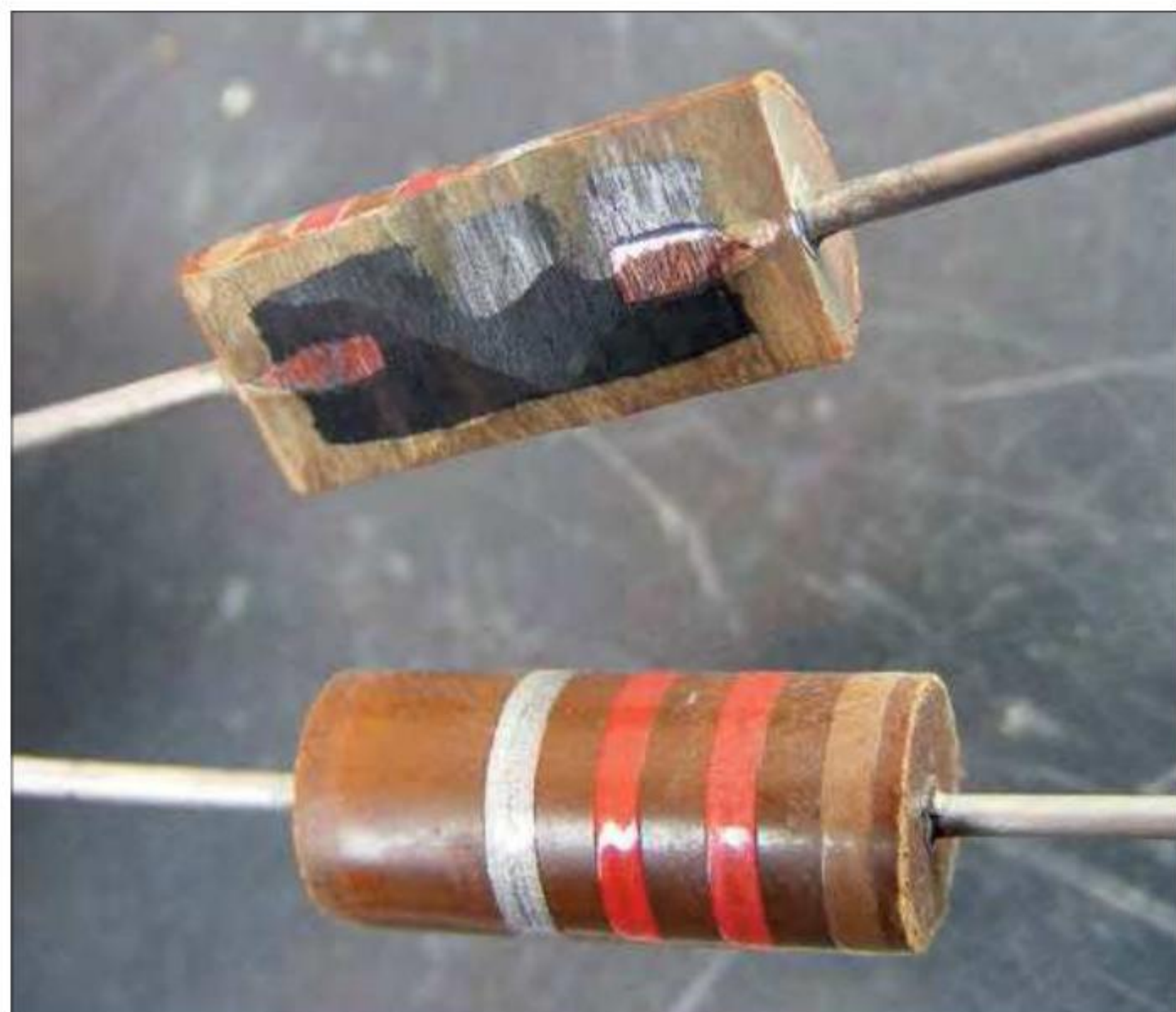


Fig.27. 1.2k Ω 2W Allen Bradley carbon composition resistors; one ground in half to show the inside construction. 24 of these resistors in parallel make an excellent 50 Ω RF dummy load because of the low inductance.



Fig.28. A common fault with Painton resistors, one of the wires has fallen off. A bit of judicious scraping with a scalpel has revealed the spiral carbon film track.

Fake news

Visual inspection is important for identifying fakes, sometimes simply revealed in the device label printing with font errors or even bad spelling. However, it can be more dramatic, such as the fake iPhone charger which blew its top across a room (see Fig.30).

Expensive audio semiconductors are often faked, especially Toshiba devices, such as the 2SC5200, shown in Fig.8. The usual clue is that the die is much smaller than the original. Good audio power transistor dies are normally at least 4x4mm.

Another common fake is the 2SK170 low-noise FET. eBay Hong Kong suppliers are the usual culprits, shown being checked in Fig.31. I've had similar issues with 2SA970s. The fake device is shown in Fig.32 and the real deal in Fig.33. Notice the different print styles. When I've sent photos and test results back to suppliers, I've always got suspiciously instant refunds along with pleading not to leave negative feedback. I tell them I'm always applying negative feedback in my work.

Voltage in vitro

Older components were often packaged in glass packages; after all, it was the

dominant encapsulation technology in the valve days of the 1960s. Because you can see inside, these glass components are great educational props, as well as objects of beauty. The triode valve shown in Fig.34 is a gem, with all the electrodes visible. I can't believe us kids used to throw them against the wall back in 1971.

Old germanium transistors were often supplied in glass SO2 encapsulations. There was a photosensitive type, the OCP70, shown in Fig.35, where the junction could easily be seen. Quartz crystals normally come in metal cans but occasionally glass ones are found, such as the one in Fig.36. Finally, one of the few components to still use a glass encapsulation are some thermistors. The classic RA53 in Fig.37 used in Wien bridge oscillators, employs an evacuated glass envelope, like a vacuum flask, to minimise heat loss from the tiny bead of resistive material.

Looking through the glass

Every so often I get a fault that has me going round in circles. One was an open-circuit OA70 diode inside the intermediate frequency transformer



Fig.29. A volume control track so worn the carbon track has disappeared in places.



Fig.30. This fake iPhone charger nearly burnt down the house.

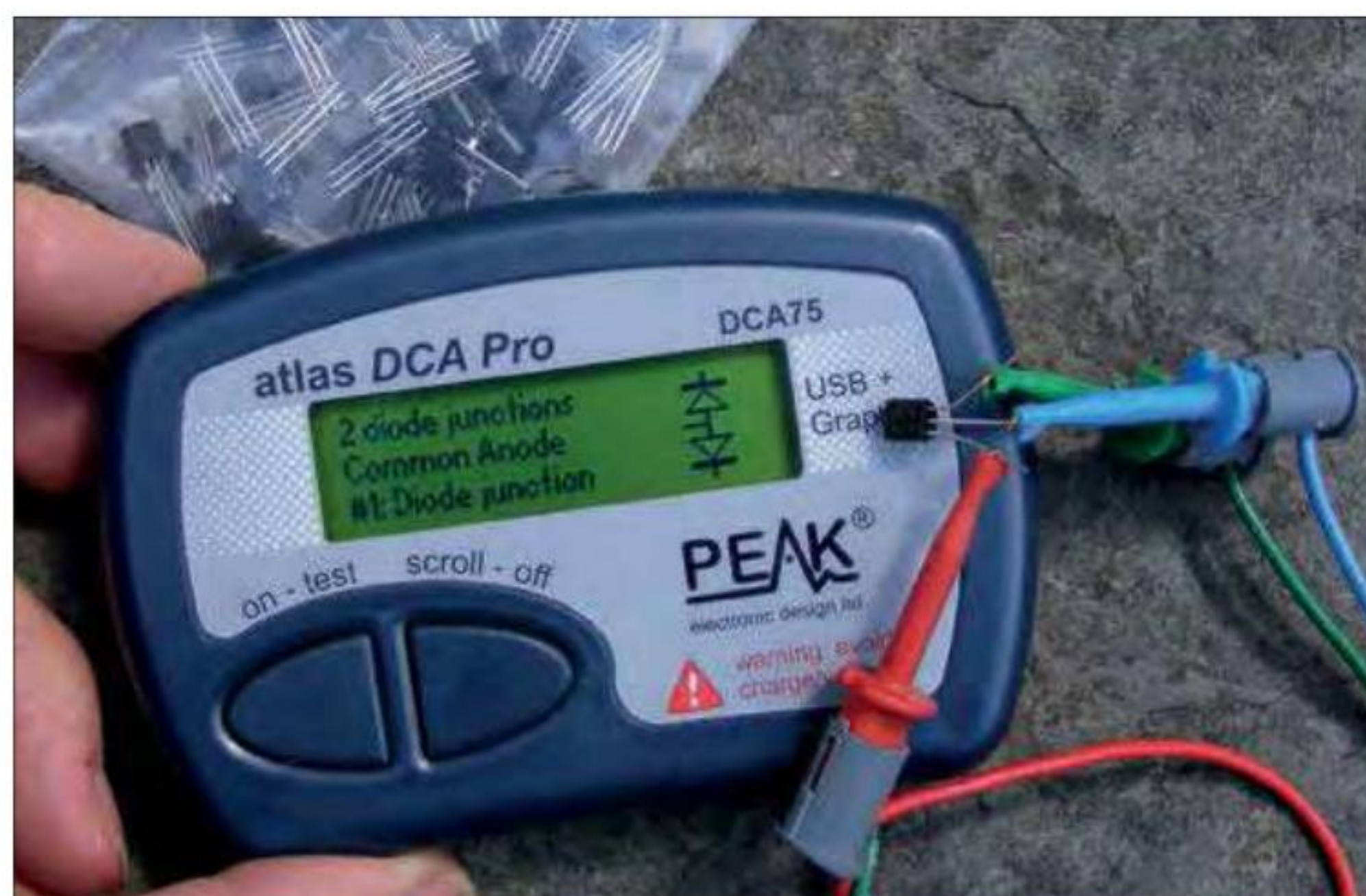


Fig.31. This bunch of 2SK170 JFETs from eBay were fakes. Watch out for odd laser writing and flashing between the legs. CA3080 and MN-series bucket-brigade delay chips fakes are also common.

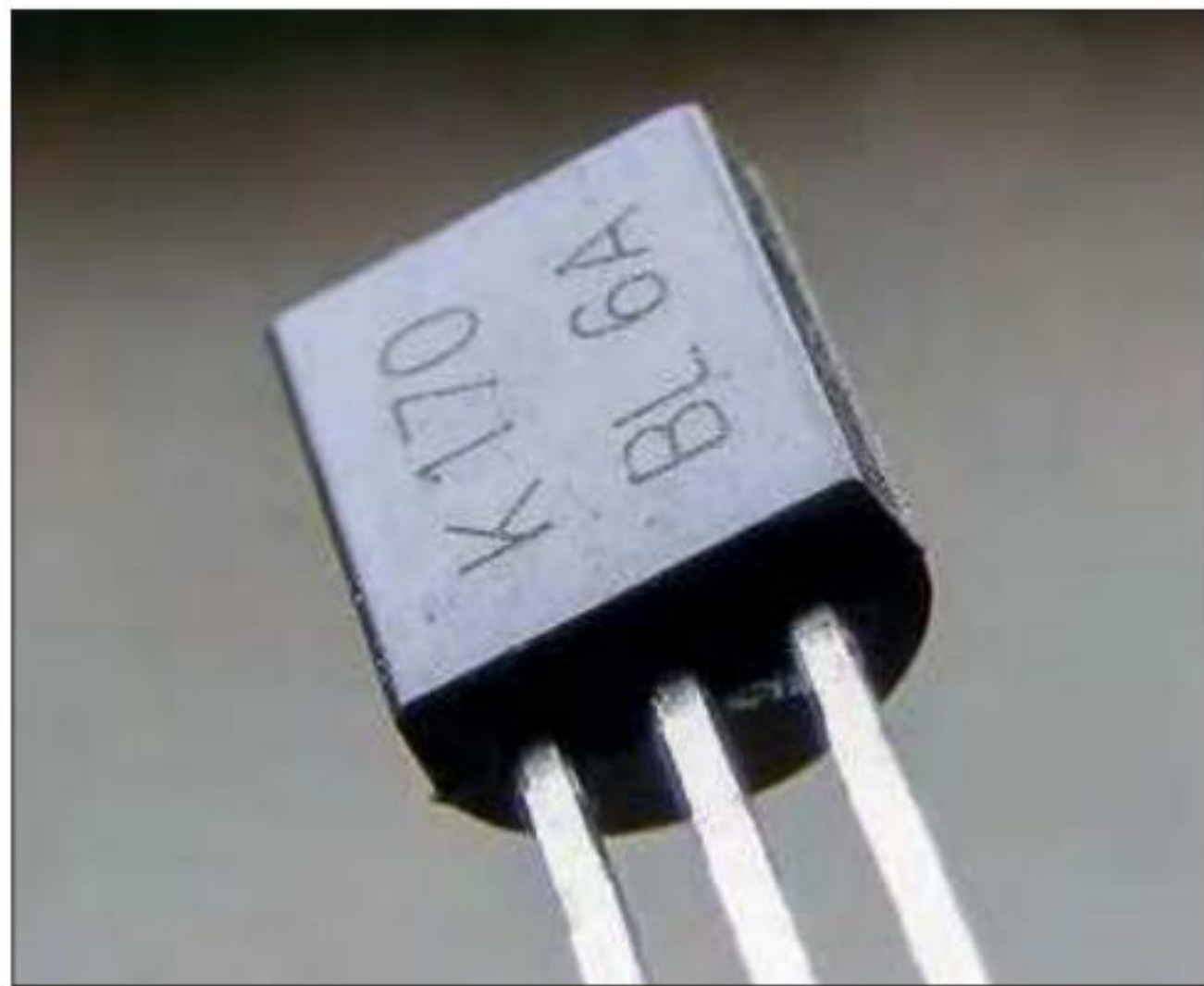


Fig.32. The fake device from Fig.31 – these constantly re-circulate on eBay at ever increasing prices.

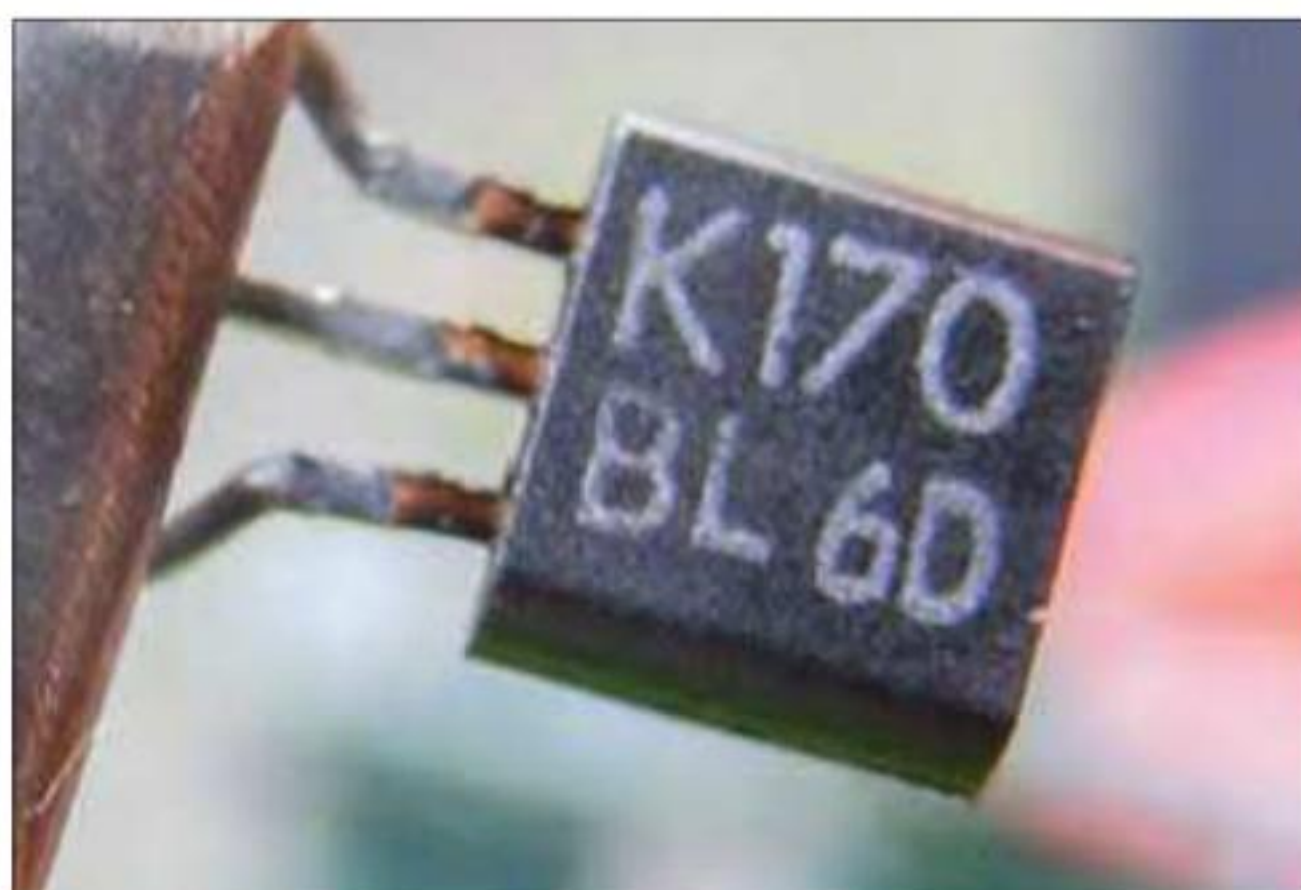


Fig.33. The real deal from Toshiba, note silver print and copper portion on lead-out wires. There's no side seam and the break-off tab at the top is central and 2.3mm wide. The dimple is 0.005-inch diameter, shallow and circular. This is the detail we have to check for in audio parts off eBay.

can of a classic Bush TR82 radio. It had languished undiagnosed on the back shelf of a local electrical shop for 20 years before I was able to fix it. The guts of the IFT, which contains the hidden black diode, are shown in Fig.38.

A recent fault was in a Fender De Lux guitar amp where no signal was getting through the input valve, an

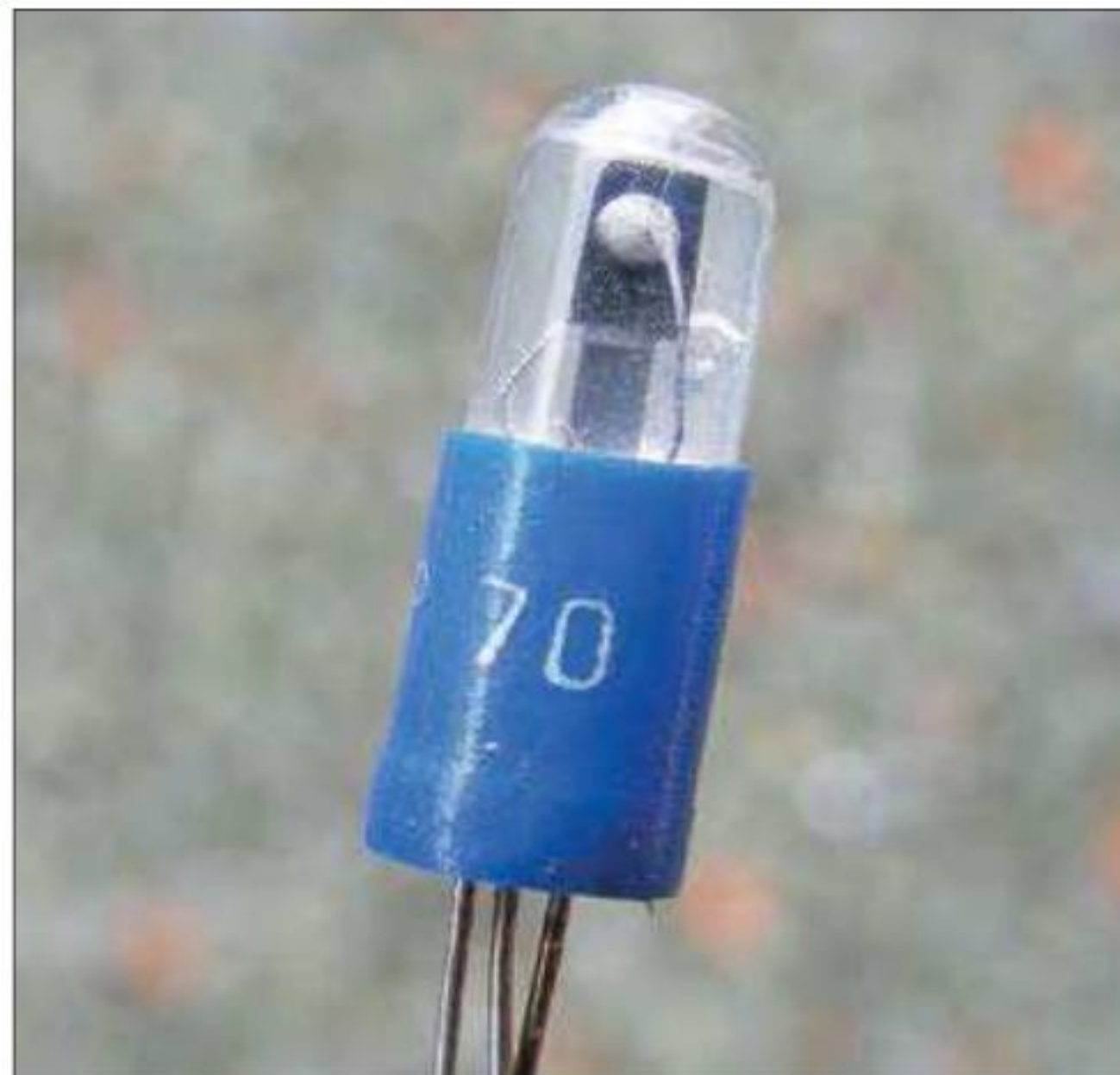


Fig.35. OCP70 phototransistor – it's shocking how imprecise and blobby the junctions were in old germanium transistors.

ECC83. Tapping the valve elicited loud bangs, so I changed it. The problem remained, so the socket appeared to be the problem. I laboriously changed the socket and it worked for three weeks. Then it stopped passing signal again. This time the valve was the problem. Two intermittent faults in the same place add up to a fault-finder's nightmare. Eventually, I found that it was a faulty internal weld linking the valve's pin to the cathode. I could see it through the glass base with a magnifying glass. I proved this after carefully crushing the glass envelope in a cloth and the link just fell off. I looked at a load of ECC83 valves and noticed the old Mullard ones had much better welding than the newer types. The moral of this story is that in electronics, using your eyes can be a very helpful technique – but do remember to protect them in the lab.

Thank you

Last, a 'thank you' to my neighbour Dr Joe Botting. All the photos marked with an '*' were taken by him.



Fig.34. A beautiful T20 triode valve from 1930. The heater, grid and anode structures can be clearly seen.

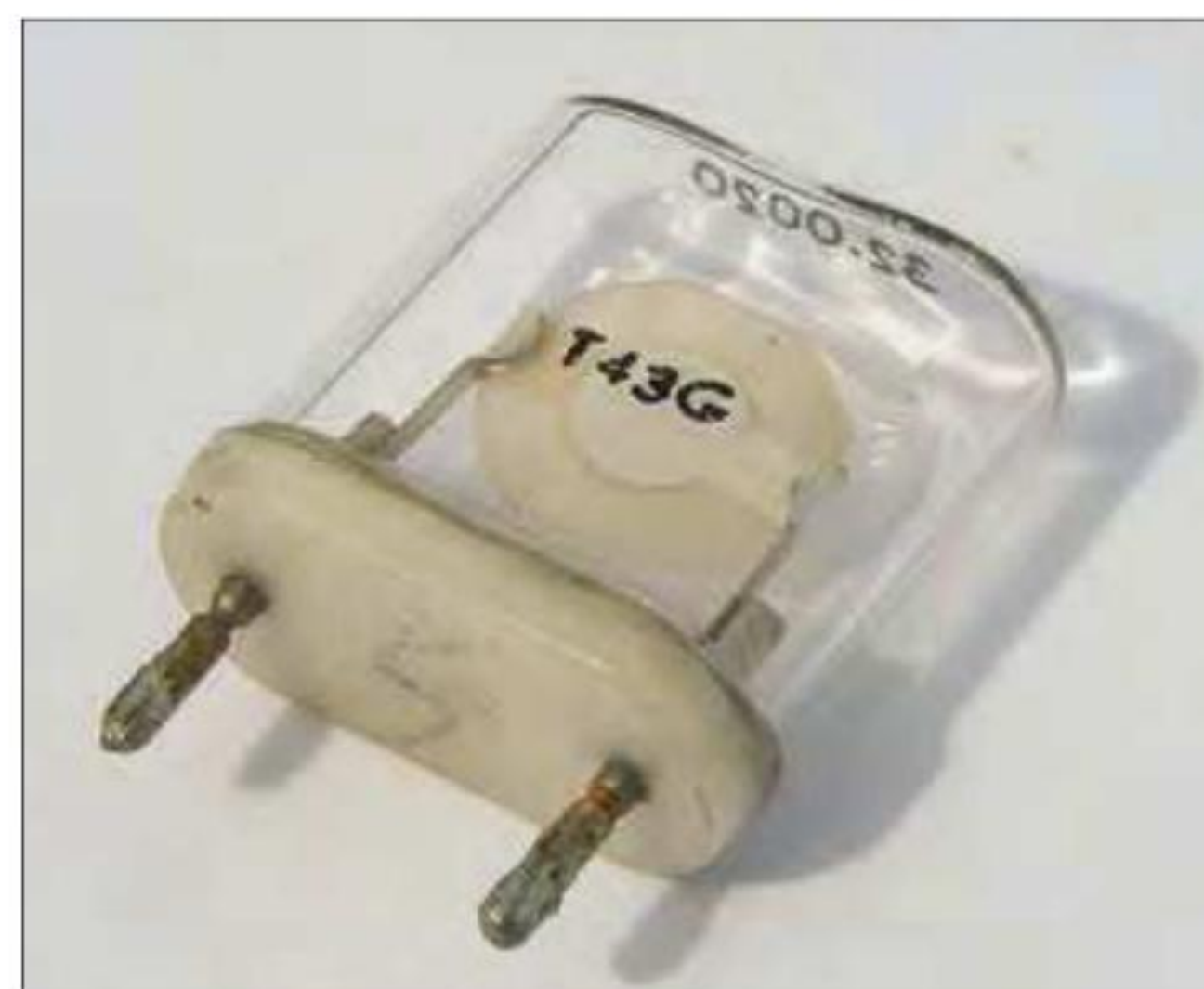


Fig.36. 35MHz quartz crystal in glass encapsulation – low-frequency examples were often made in B7G valve envelopes.



Fig.37. A glass RA53 thermistor, much loved by builders of audio oscillators.

WARNING!

When disassembling electronic equipment or components, you must work with:

- Eye protection
- Fume extraction
- Safe wiring/earthing
- Comprehensive understanding of any chemicals and materials in use

These are not nice-to-have optional extras – you must follow all safety guidelines to protect yourself and those around you.

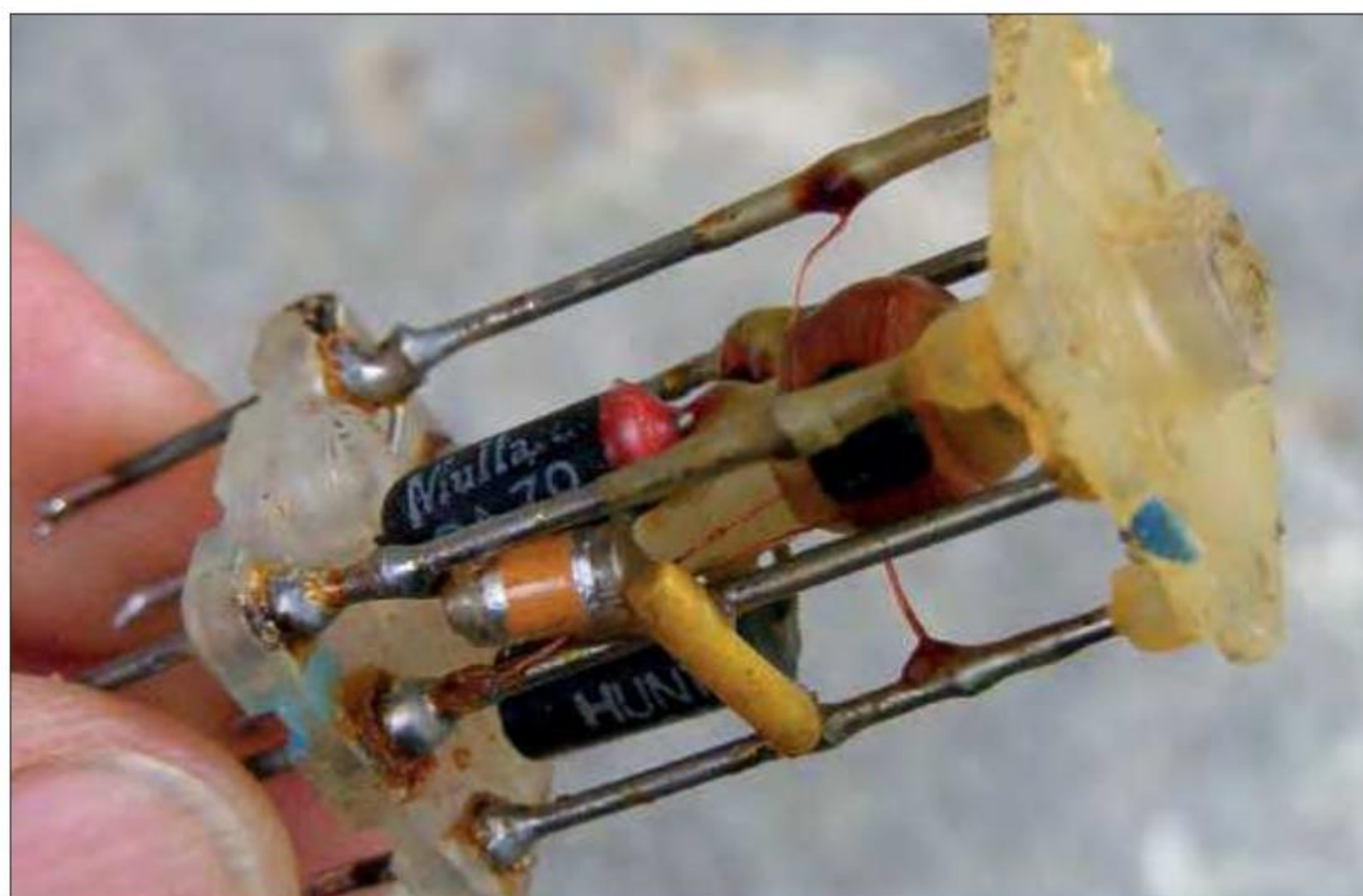


Fig.38. The final IFT (intermediate frequency transformer) of a Bush TR82 radio with its screening can removed. The open-circuit OA70 diode that had eluded discovery for over 20 years was hiding inside. I now install replacement diodes on the pins under the chassis rather than taking the IFT out and opening it up.

Circuit Surgery

Regular clinic by Ian Bell

Multistage log amplifiers for RF power measurement

The August edition of **PE** featured a low-cost wideband digital *RF Power Meter* by Jim Rowe. This is based around the AD8318 1MHz to 8GHz, 70dB Logarithmic Detector/Controller IC from Analog Devices. The project uses a modified version of a pre-built module, but essentially the key analogue functionality of the project is based on the AD8318 IC. These pre-built modules are a great way of using a large range of advanced ICs without having to worry about the difficulties of designing a PCB and soldering the often very small surface mount devices needed for an optimum layout. In the project, instrument functionality is provided by software running on an Arduino Nano, which receives a digitised version of the AD8318's output via an LTC2400 DAC. The article provides a brief description of the AD8318, but there is insufficient space to go into its principles of operation in much depth, so that is the topic of this month's *Circuit Surgery*. We will explain the basics of how this class of ICs work (Analog Devices produce several devices based on similar principles, not just the AD8318), illustrating the theory with some idealised LTspice simulations based on behavioural sources. Before getting into how the AD8318 works, it is worth discussing RF power measurement in general, as there are some potential points of confusion.

Signal power measurement

An electrical signal producing a voltage V across, and a current I through a load delivers instantaneous power of $P = VI$ to the load. If the load is a resistance of value R we can also express the power as $P = V^2/R$ or $P = I^2R$ by substituting for I or V using Ohm's law ($V = IR$, $I = V/R$). So, if we know R , then we can obtain power values

just by measuring voltage (or current). In RF systems the signal path is usually matched to a specific impedance (for example 50Ω) so it is possible to obtain signal power from voltage measurements. This is the assumption used in the *RF Power Meter* project, which has a nominal input impedance of 50Ω .

The power dissipated in a resistor driven by a signal such as a sinewave varies from instant to instant in accordance with the equations given above; however, we often need to know the average power over a period of time (at least one cycle). This applies to signal strength indicators (eg, on your mobile phone), or instrumentation such as the *RF Power Meter* project, but also in the internal circuitry of radio systems. For example, received radio signal strength varies considerably and it is often necessary to adjust the gain of parts of the system to accommodate this (AGC, or automatic gain control) – this requires accurate signal strength measurement.

As discussed, with a fixed/assumed load we can obtain power from voltage, but finding average power for an AC signal is not simply a matter of taking the average voltage or current – it is zero for a sinewave over any whole number of cycles. The heating effect produced in a resistor forms the basis of how we define power for non-DC signals – AC power is equal to the DC power which would produce the same heating effect in a resistor. For a fixed R , this can be obtained by averaging V^2 over time ($P = V^2/R$). If we take the square root of the average of V^2 we get a value called the 'Root Mean Square' (RMS) voltage – this is the DC voltage, which, if applied across the load, would result in the same power dissipation as that produced by our AC signal.

For a cyclic waveform of fixed shape (eg, sine, triangle and square) there is a fixed relationship between the peak voltage and the RMS value, which is known as the crest factor. Mathematically, this can be obtained by integrating the square of the waveform function over one cycle, but of course the results are well known for common waveforms. For a sinewave $V_{\text{peak}} = \sqrt{2} \times$

$V_{\text{RMS}} = 1.4142 V_{\text{RMS}}$ (the crest (C) factor is 1.4142). The crest factor for a triangle wave is: $C = \sqrt{3} = 1.7321$, and for a square wave, $C = 1$. These values apply to waveforms which are undistorted and symmetrical about 0V.

If we know or assume the waveform shape and have a fixed, known load resistance it follows that we can obtain power from a measurement of peak voltage (or average peak voltage over multiple cycles). The average power is V_{RMS}^2/R – which can be found from the average peak voltage by an appropriate scaling obtained from R and the crest factor. However, if the waveform is of arbitrary shape and we need a 'true RMS' measurement then the process is more complex. The AD8318 IC, and hence the *RF Power Meter* project on which it is based, do *not* measure true RMS.

Decibels

Power in RF systems is typically expressed in dBm units – this is power in decibels (dB) referenced to 1mW – this is the measurement unit used by the *RF Power Meter* project. The decibel is based on the logarithm of the power ratio of two signals (say P_1 and P_2). If we are interested in gain or attenuation (input-output relationship) then the two signals are obviously the input and output. However, to use decibel units for expressing the power of an individual signals one of the power values must be a fixed reference, and the units are written to express this (eg, dBm for 1mW reference and dBW for 1W reference).

Decibels are useful because their logarithmic nature means very large ranges of power levels are compressed into a small range of decibels values. An instrument, such as the *RF Power Meter* which responds directly to the decibel signal level is able to handle a very wide range of signal power. Using decibels on graph scales allows details to be seen at both large and small signals levels (the small level details would be lost on a linear graph). When considering signal paths, expressing gain and attenuation in decibels makes calculations

Simulation files

Most, but not every month, LTspice is used to support descriptions and analysis in *Circuit Surgery*. The examples and files are available for download from the *PE* website.

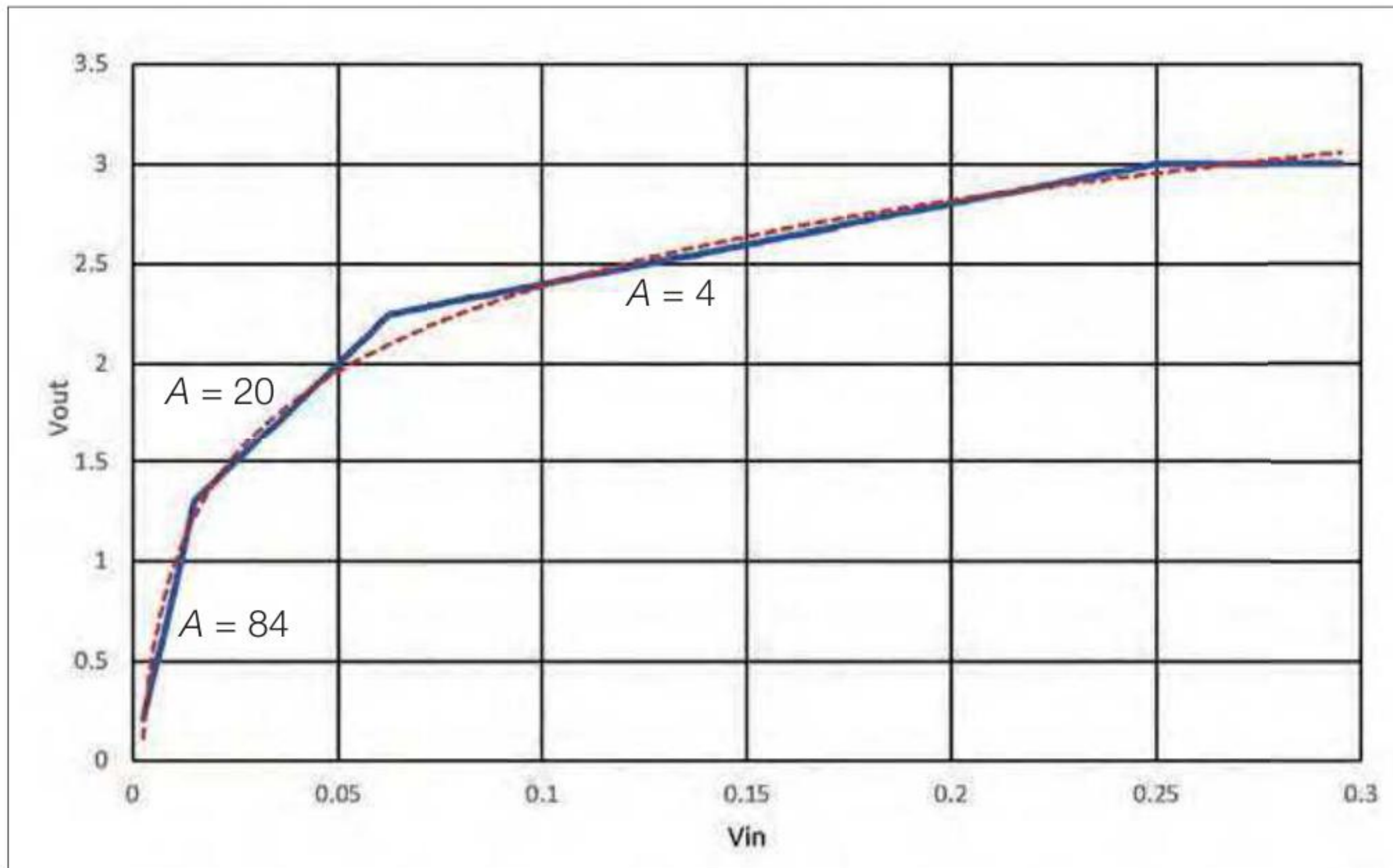


Fig.1. Piecewise-linear approximation (solid blue line) to a logarithmic (dashed red line) input-output relationship.

straightforward – the multiplication of gain or attenuation stages is translated to addition or subtraction in the logarithmic world of the decibel.

A power ratio in decibels is given by $10\log_{10}(P_2/P_1)$ dB, where P_1 is the reference level (for example 1mW) and P_2 is the value we are measuring. The term ‘decibel’ means one tenth (*deci*, hence d) of a bel (symbol B). One bel is $\log_{10}(P_2/P_1)$, but as we use $10\log_{10}(P_2/P_1)$ we are counting in tenths of a bel. The bel is named after Alexander Graham Bell.

We can also use decibels to express voltage levels. Given that $P = V^2/R$, if we consider a power ratio involving the same R then $P_2/P_1 = V_2^2/V_1^2$ as both instances of R cancel in the ratio. If we square something inside a logarithm it is equivalent to multiplying the log by two (without the square). That is $\log(x^2) = 2\log(x)$. So, to express a voltage in decibels we use $20\log_{10}(V_2/V_1)$. Note that we are multiplying by 20, not by 10 as we did with the power ratio. Again, for signals levels rather than gains, we need to indicate the reference level (for example dBV is referenced to 1V).

Demodulating log amplifiers for power measurement

We can write an expression for the average power of a signal in terms of dBm, related to the RMS voltage of a signal (V_{RMS}). Using $P_2 = V_{RMS}^2/R$ and $P_1 = 1\text{mW}$:

$$P_{dBm} = 10\log_{10}(V_{RMS}^2/R / 1\text{mW})$$

Note that R is not cancelled in this equation, so we should state the value used (for example, 50Ω). For a fixed waveform with a known crest factor we have:

$$V_{peak} = C \times V_{RMS}, \text{ so:}$$

$$V_{RMS}^2 = (V_{peak}/C)^2$$

$$P_{dBm} = 10\log_{10}((V_{peak}/C)^2/R / 1\text{mW})$$

For a sine wave into 50Ω, with $C = \sqrt{2}$ and $R = 50\Omega$ we get:

$$P_{dBm} = 10\log_{10}(V_{peak}^2/2 \times 50 \times 0.001) \\ = 10\log_{10}(V_{peak}^2/0.1)$$

Dividing inside a logarithm is equivalent to subtraction of logs, so:

$$P_{dBm} = 10\log_{10}(V_{peak}^2) - 10\log_{10}(0.1) \\ = 10\log_{10}(V_{peak}^2) - 10$$

Using voltage rather than its square:

$$P_{dBm} = 20\log_{10}(V_{peak}) - 10$$

Thus, if we build a circuit with an input impedance of 50Ω that produces an output proportional to the logarithm of the peak value of the input signal we obtain an output voltage which is proportional to the power in dBm. There is an offset (10 in the above equation) which is easily accounted for in calibration. The crest factor just changes this offset, so calibration could be done for different fixed wave shapes. Similarly, the input impedance also changes the offset in the above equation, but for a real implementation this has to be correctly matched, which would usually be to the reference impedance.

The key thing here is the logarithmic response to the peak input voltage

– which is exactly what is provided by the AD8318 and various other similar devices. Responding to the peak means that the output tracks the log of the envelope of the input waveform amplitude. This is similar to the process of detection or demodulation in AM radio receivers, so these types of circuit are referred to as detecting or demodulating logarithmic amplifiers.

Piecewise log amplifiers

There is more than one way to make a circuit with a logarithmic response. A common approach for DC or low frequencies is to use the exponential current-voltage relationship of a diode or transistor in an op amp feedback loop. However, for high frequencies such as those targeted by the AD8318 a piecewise-linear approximation is often used instead. The circuit has a gain which varies over segments of the input range and so appears as a series of straight-line segments when the input-output relationship is plotted. This is illustrated in Fig.1, where the piecewise-linear approximation is the set of solid blue lines, which closely approximates the true logarithmic function shown by the dashed red line.

The piecewise response in Fig.1 has its highest gain ($\times 84$) for small inputs (the gain is the slope of the graph, so a steeper slope is a higher gain). At a certain point (about $V_{in} = 16\text{mV}$ in Fig.1) the gain reduces from $\times 84$ to $\times 20$. This segment is longer than the first one, extending for about 47mV to $V_{in} = 63\text{mV}$. The third segment has an even lower gain of $\times 4$ and covers a longer range again, up to about $V_{in} = 250\text{mV}$. Above this input voltage the output limits at a fixed 3V. The piecewise response in Fig.1 approximates the logarithmic function quite well over the range 3 to 300mV. For higher input voltages the saturated (fixed final output level) would deviate more and more from the log function as the input level and hence log of the input increased. For very small input voltages the log function would produce large negative values. A real circuit will only produce a log response over a limited range.

The piecewise log response can be implemented by using a cascade of output-limited amplifiers with their outputs summed, as shown in Fig.2

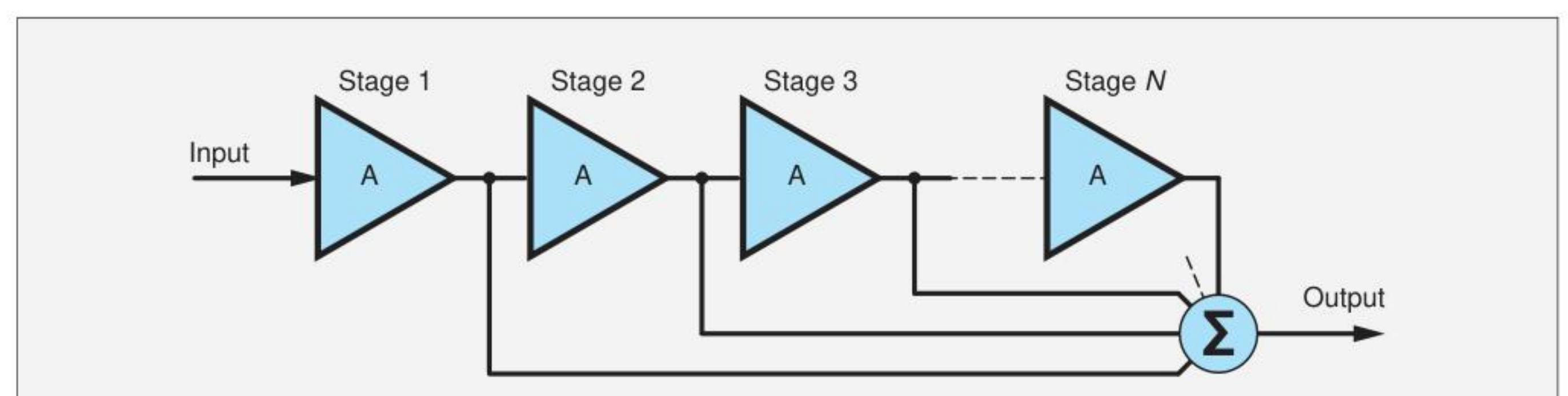


Fig.2. A cascade of N limiting amplifiers with summed outputs, which approximates a logarithmic response.

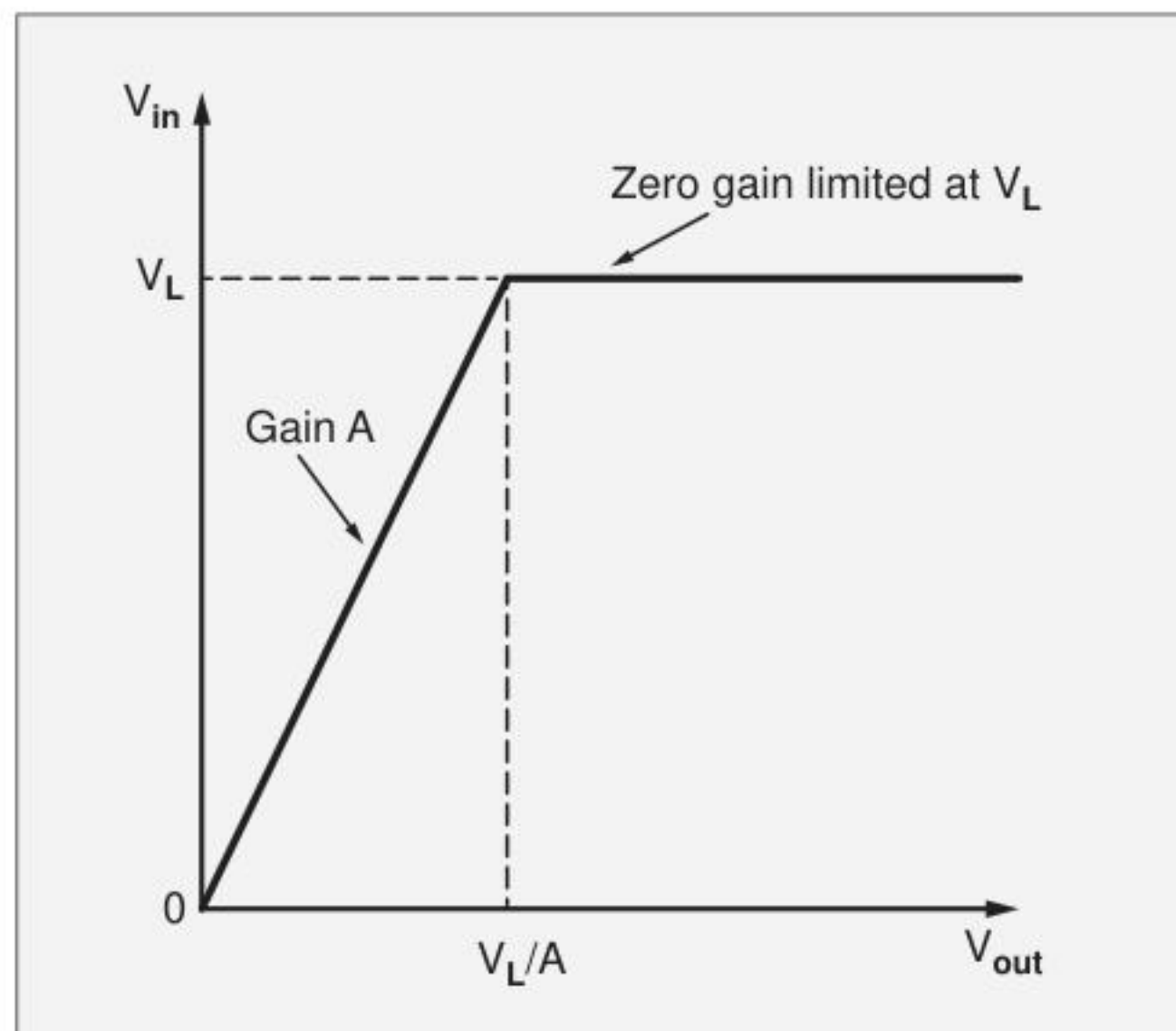


Fig.3. Transfer function of a limiting amplifier with gain A and output limit V_L .

– this form of circuit structure is used in the AD8318. The amplifiers have gain A until the output reaches a limiting voltage (V_L), above this the gain is zero. Inputs greater than or equal to V_L/A produce an output limited at V_L . The input-output relationship of the limiting amplifier is shown in Fig.3 – this is for positive inputs, for negative inputs the output limits at $-V_L$.

If a sufficiently small input signal is applied to the circuit in Fig.2 none of the amplifiers will limit and the gain to the final output will be A^N , for example with three stages the gain is $A \times A \times A = A^3$. The penultimate stage output has a gain of $A^{(N-1)}$, the one before that $A^{(N-2)}$, and so on. These outputs are summed; so, for example, the total output with three stages is $(A^3 + A^2 + A)V_{in}$. If $A = 4$ then the gain is $(4^3 + 4^2 + 4)V_{in} = (64 + 16 + 4)V_{in} = 84V_{in}$, the same as the first segment in Fig.1.

If the input signal is increased to the point where the output of the penultimate amplifier is equal to V_L then at this, and higher inputs, the final amplifier will limit. This occurs at $A^N V_{in} = V_L$, or $V_{in} = V_L/A^N$, for example, with three stages, and $V_L = 1$ at $1/64 = 16\text{mV}$ – the end of the first segment in Fig.1. Under these conditions the final amplifier will contribute a constant V_L to the summed output. For three stages, the output will be $(A^2 + A)V_{in} + V_L$. If $A = 4$ and $V_L = 1$ this segment will have the function $20V_{in} + 1$, starting at $V_{in} = 16\text{mV}$, so V_{out} at this point is $20 \times 0.016 + 1 = 1.3\text{V}$, as seen on Fig.1.

The next segment occurs when the penultimate amplifier limits at $A^{(N-1)}V_{in} = V_L$. For three stages, the second amplifier limits at V_L/A^2 , which for $A = 4$ and $V_L = 1$ is at $V_{in} = 1/16 = 63\text{mV}$ – the end of the second segment in Fig.1. In this segment the last two amplifiers are contributing a constant V_L to the output. For three stages this will be $AV_{in} + 2V_L$. For $A = 4$ and $V_L = 1$ this (third) segment will have the function $4V_{in} + 2$, starting at $V_{in} = 63\text{mV}$, so V_{out} at this point is $4 \times 0.063 + 2 = 2.3\text{V}$, as seen on Fig.1.

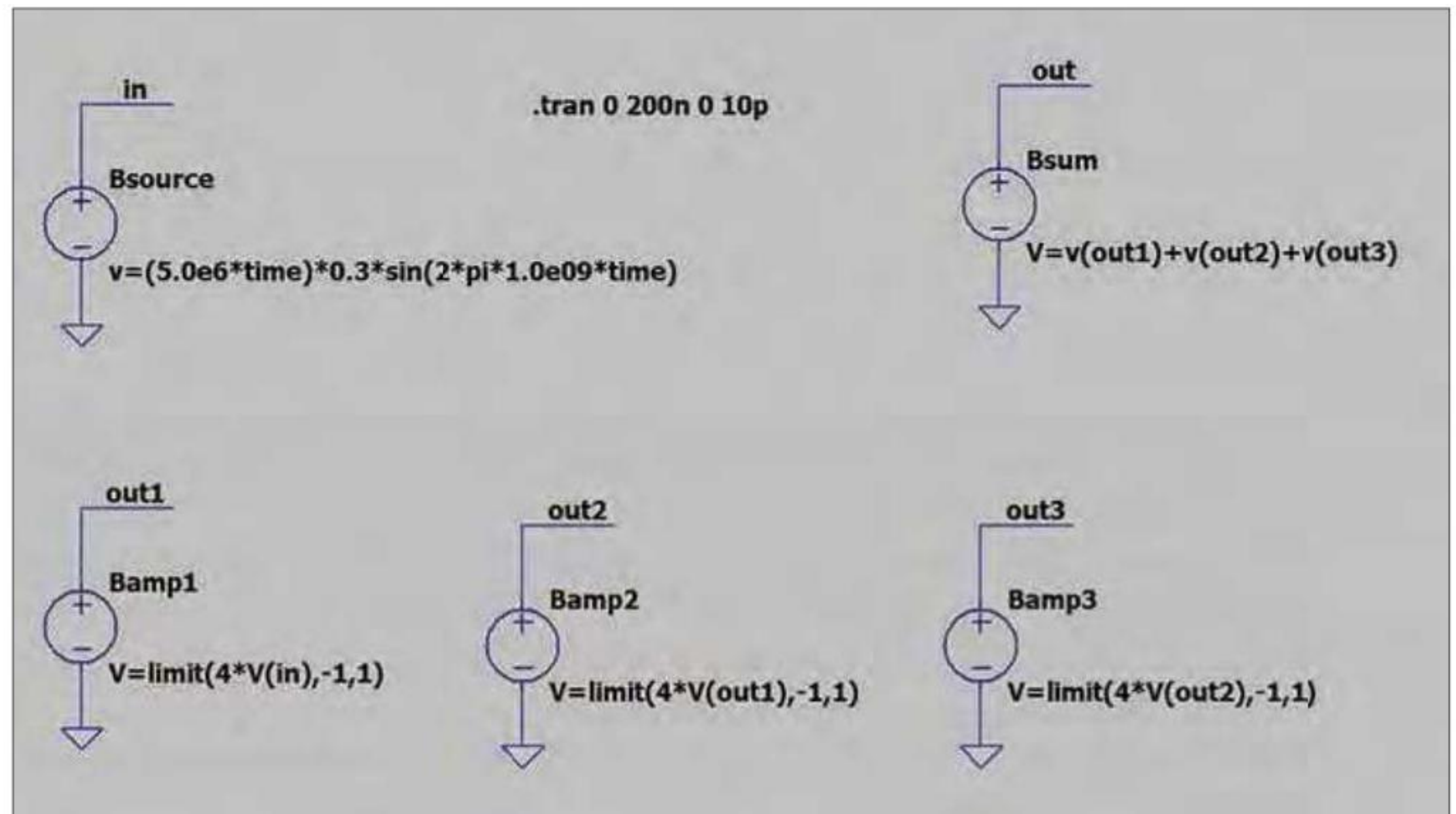


Fig.4. LTspice behavioural simulation of a summed cascade of limiting amplifiers.

With a sufficiently large input ($V_{in} \geq V_L/A$) the first amplifier, and all the others in the cascade, will limit and the summed output will limit at NV_L . For our example, with $N = 3$, $A = 4$ and $V_L = 1$ this occurs at $V_{in} = 1/4 = 250\text{mV}$. Above this input voltage, the output is constant at $3V_L = 3\text{V}$. Again, this is seen in Fig.1. The preceding discussion has shown that the circuit in Fig.2 can produce the piecewise approximation to a log function shown in Fig.1. This example used just three stages, which is sufficient for illustration, but much better

performance can be obtained with more stages – the AD8318 has nine.

LTspice Behavioural Simulation

We can simulate an idealised version of the amplifier cascade in LTspice using behavioural sources. These are voltage or current sources for which we can write equations – the output of the source can be expressed as a mathematical function of other voltages and currents in the circuit, time and the constant π . For example, we can model an amplifier with gain 4 by using

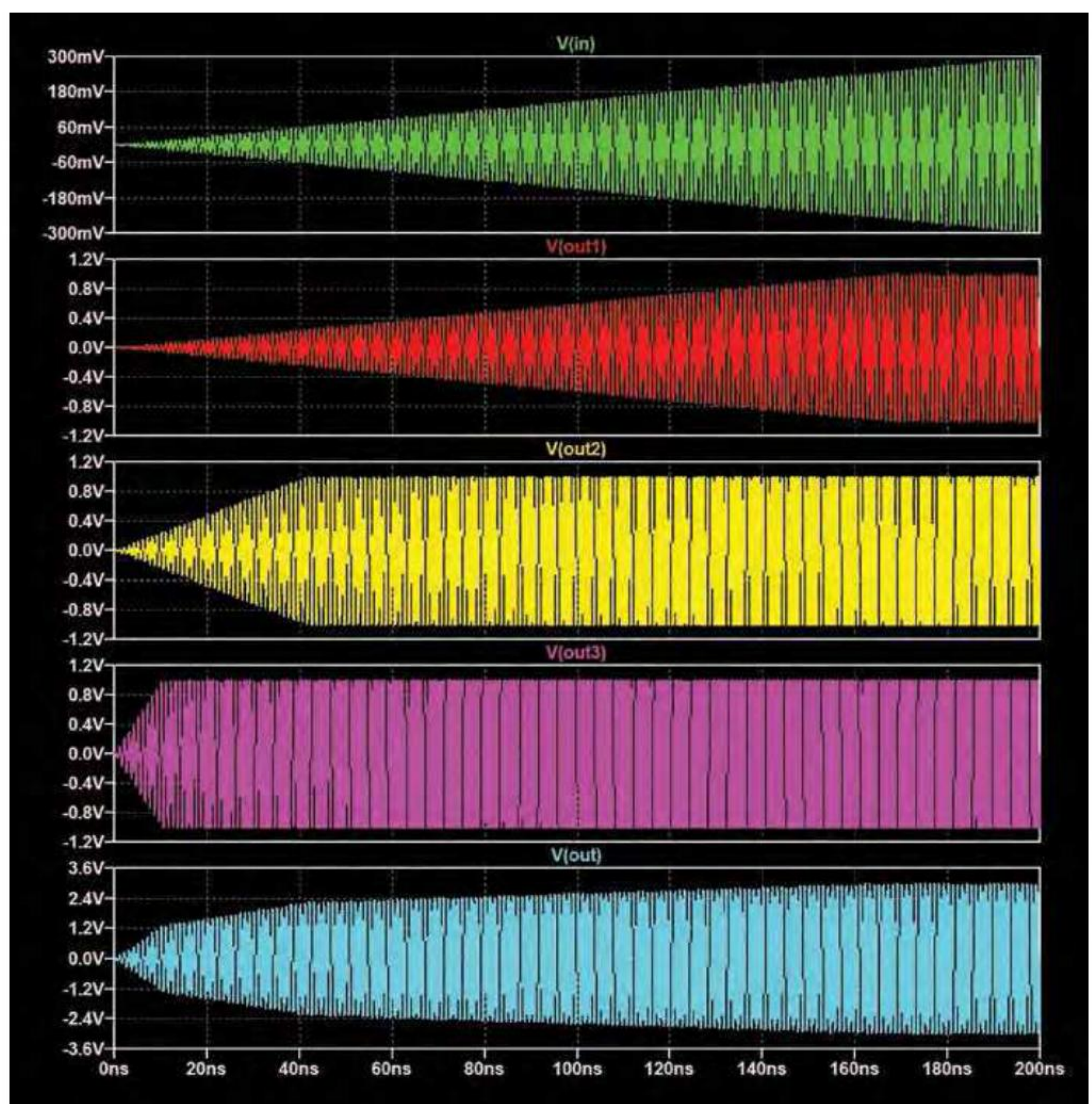


Fig.5. Simulation results for the circuit in Fig.4.

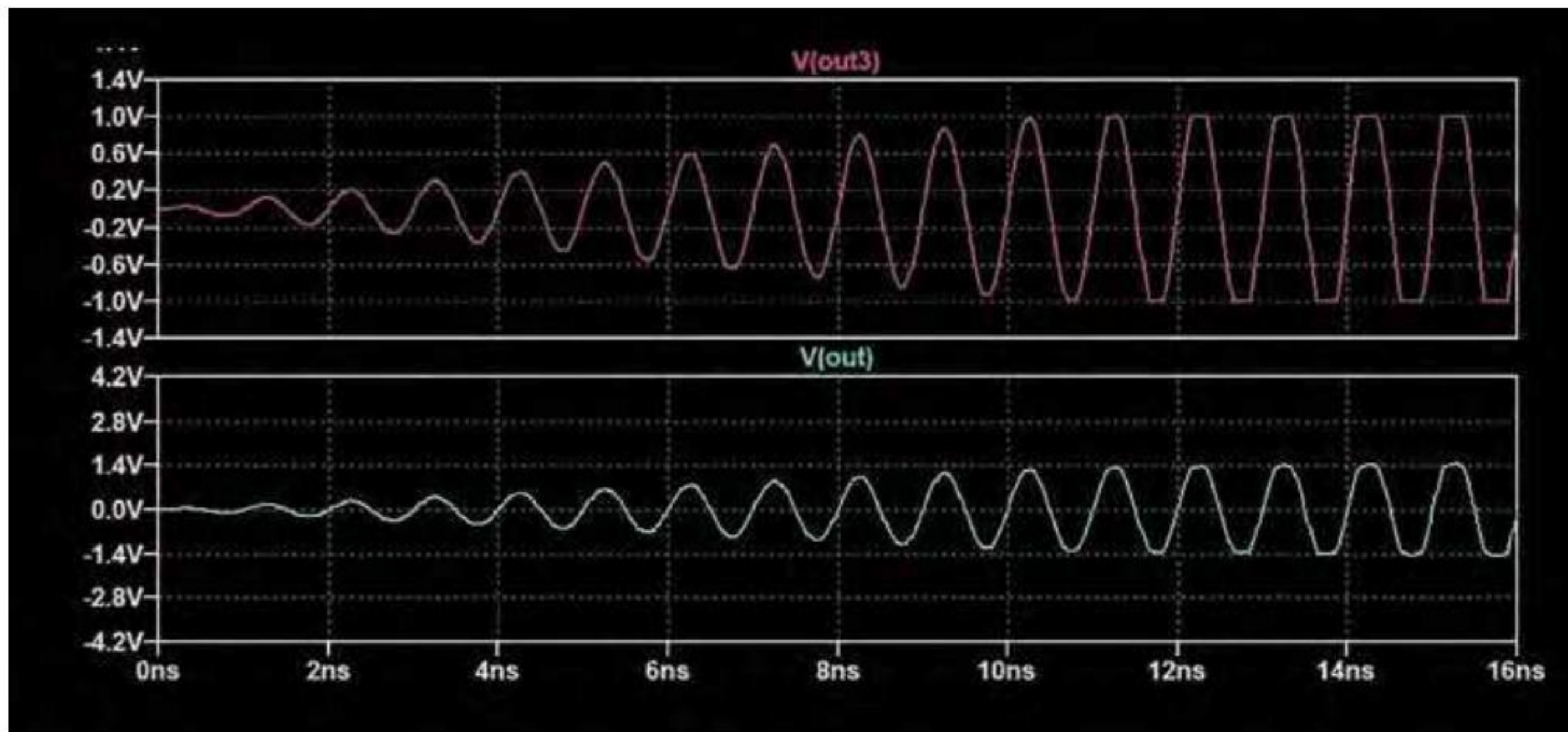


Fig.6. Zoom-in on two of the signals in Fig.5.

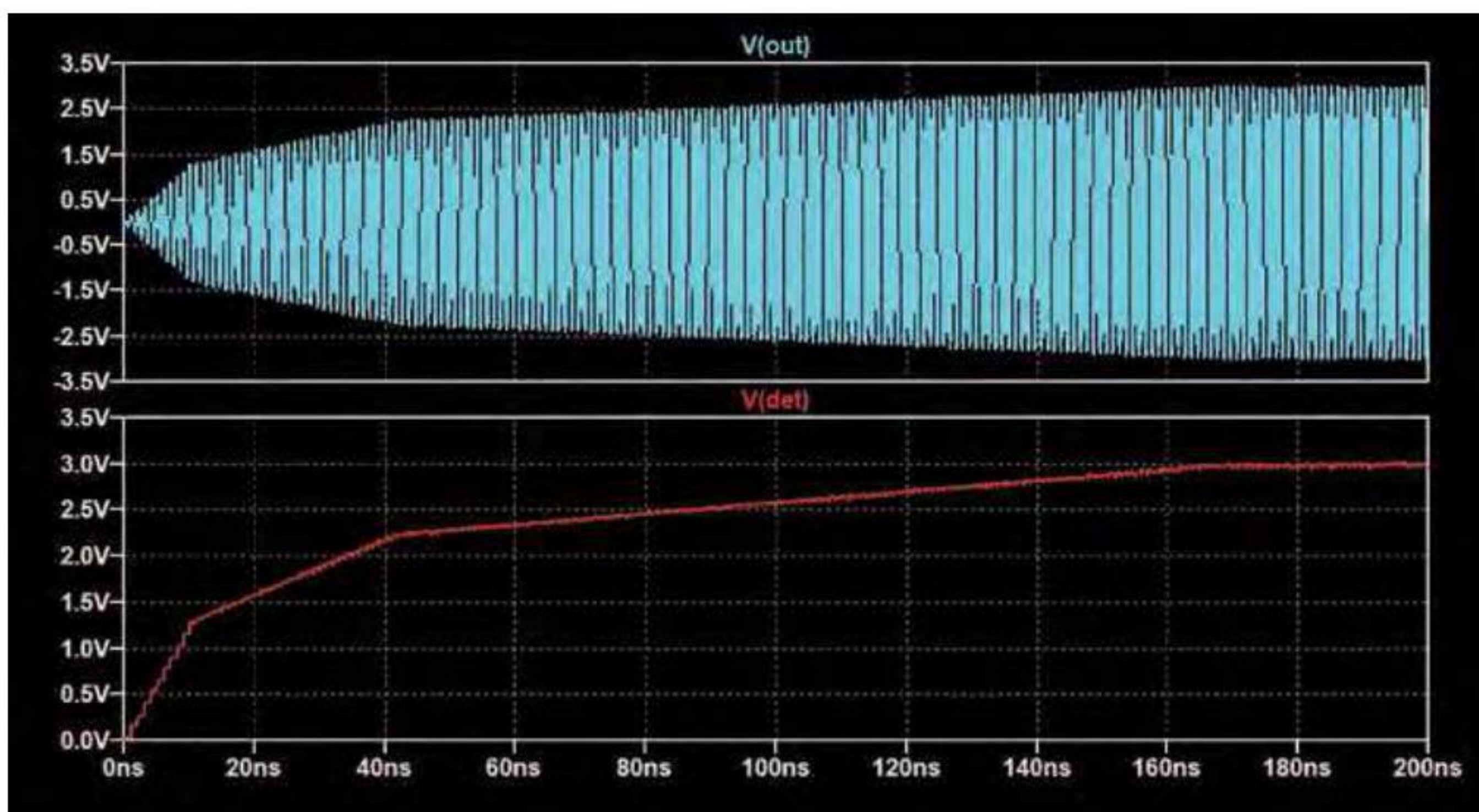


Fig.8. Simulation results for the circuit in Fig.7 – $v(\text{det})$ follows the envelope of $v(\text{out})$.

a behavioural source with the equation $V=4 \cdot V(\text{in})$. The output of the source will be four times the voltage on node in . To create a limiting amplifier, we can use the `limit` function. The output from LTspice function `limit(x,min,max)` is x if x is between min and max , otherwise it limits to either min or max , depending on which value is exceeded.

We can use $V=\text{limit}(4 \cdot V(\text{in}), -1, 1)$ to produce an amplifier of gain 4, limiting its output to $\pm 1\text{V}$, as used in the previous discussion. The LTspice schematic in Fig.4 has three such amplifiers (`Bamp1`, `Bamp2` and `Bamp3`) cascaded (eg, the output of `Bamp1` is on node `out1`, which is the input to `Bamp2`). Another behavioural source (`Bsum`) is used to add the three outputs from the amplifier together. To see the response of the circuit we create a 1GHz sinewave input signal which increases in amplitude linearly from 0V to 300mV (the same input range as in Fig.1) in 200ns.

The results of the simulation are shown in Fig.5. The simulation is over so many cycles of the 1GHz sine wave that the waveform detail cannot be shown – the plots show blocks of colour, with the shape of the blocks following the envelope of the signal amplitude. As the input ($v(\text{in})$) increases the three

amplifiers limit in turn (the final amplifier output $v(\text{out3})$ limits first). We see their output amplitudes increase linearly until the 1V limit is reached in each case. The summed output envelope ($v(\text{out})$) follows the shape of the piecewise curve in Fig.1. Fig.5 is a zoom-in of the first part of the $v(\text{out3})$ and $v(\text{out})$ waveforms

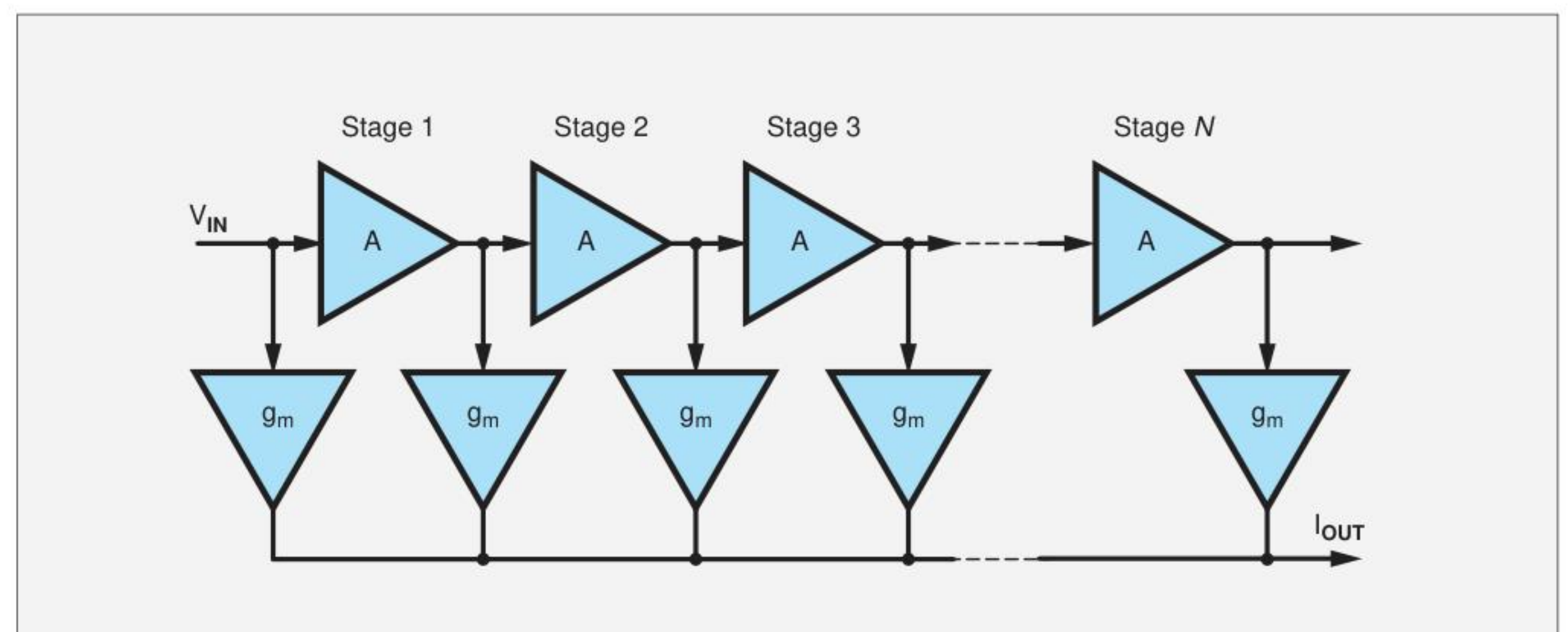


Fig.9. Using transconductance amplifiers to sum the amplifier cascade outputs.

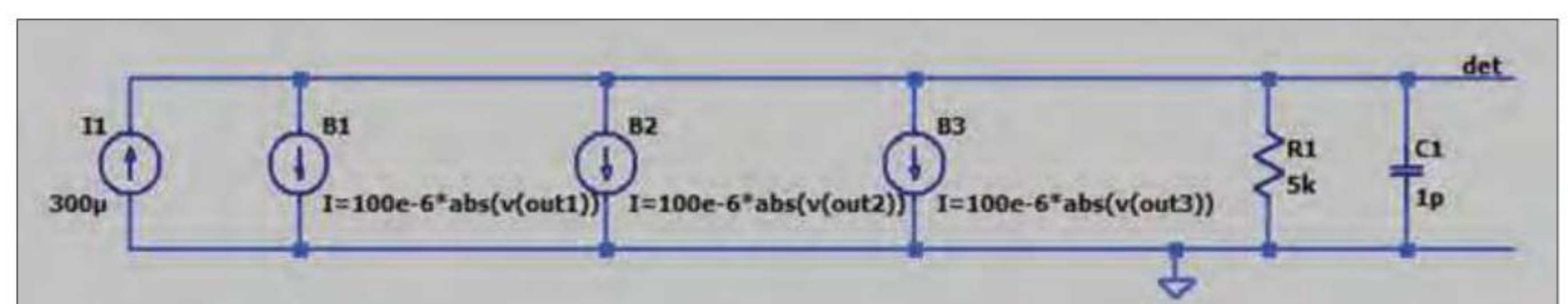


Fig.10. Absolute value transconductance, current summing and filtering circuit (part of the LTspice schematic).

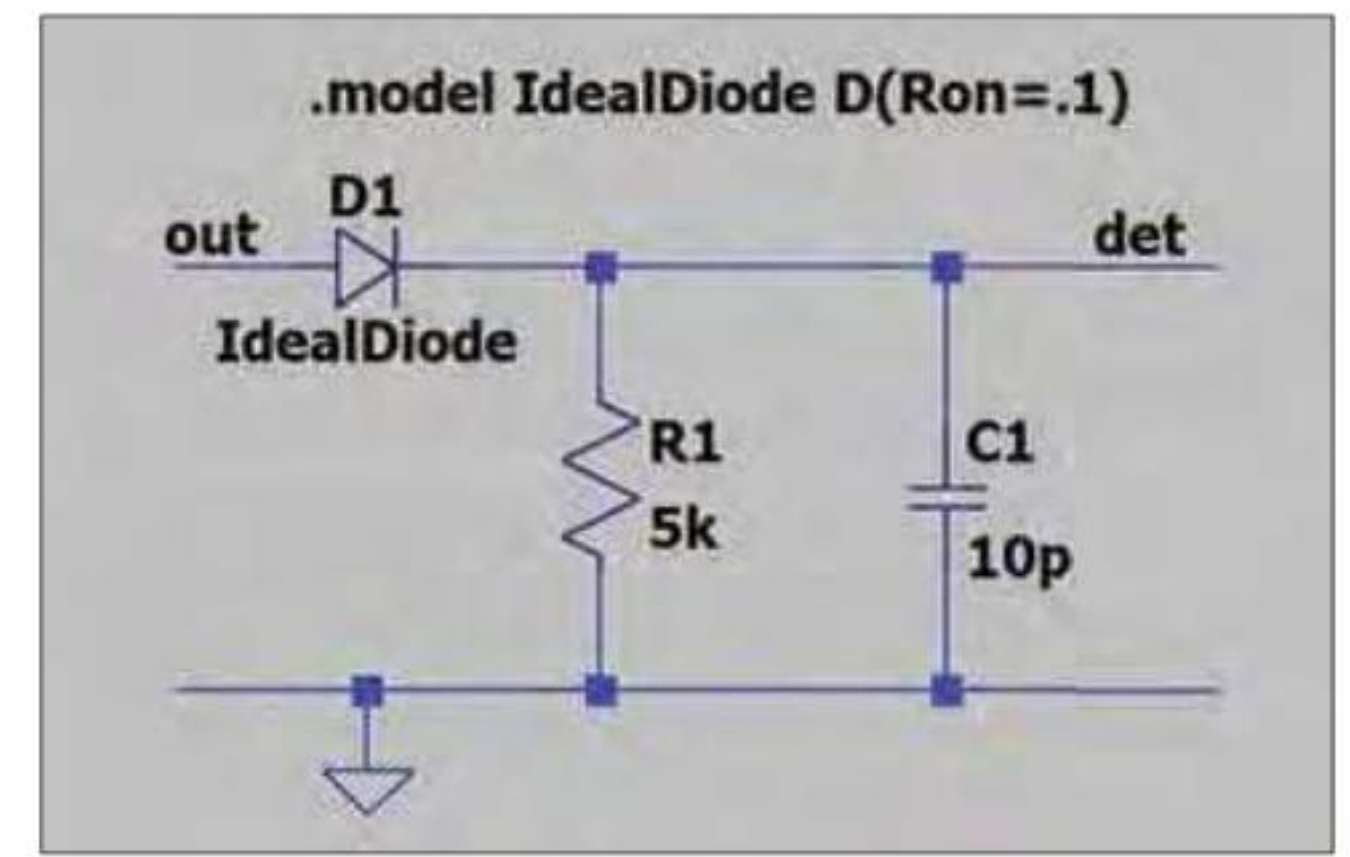


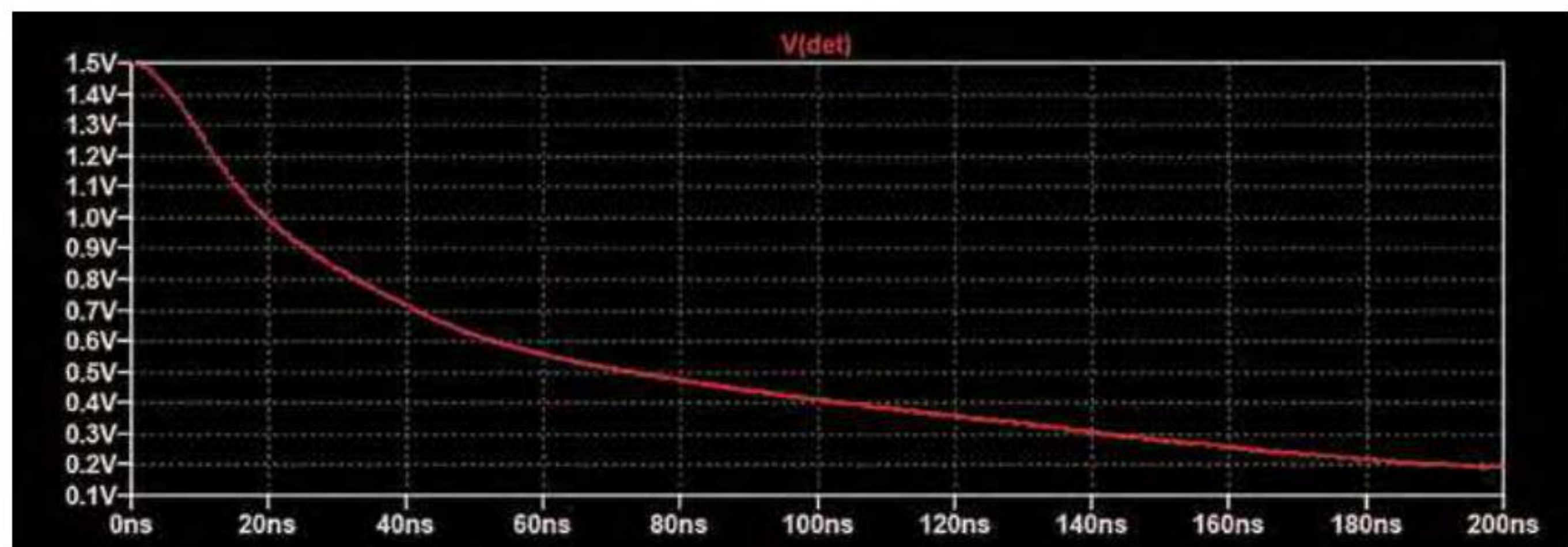
Fig.7 Diode envelope detector circuit (part of the LTspice schematic).

showing the sinewave signal clipping as `Bamp3` goes into limit.

Envelope Detector

The circuit described so far has a logarithmic gain response but does not do all we need to implement the *RF Power Meter* – specifically, it just amplifies the input signal, it does not output a voltage equal to the peak value. A simple way to obtain the peak (but not that used by the AD8318) is to use a half-wave rectifier and RC filter – a diode detector, or envelope demodulator, often associated with basic AM radio circuits. To do this, the circuit in Fig.7 is added to the schematic in Fig.4 (Fig.7 only shows the detector, the rest of the schematic is the same as Fig.4). The diode is idealised – it has zero forward-voltage drop. The simulation results with the detector are shown in Fig.8, in which $v(\text{out})$ is the same as in Fig.5. The output voltage $v(\text{det})$ follows the envelop of the $v(\text{out})$ waveform, which due to the linear input amplitude sweep, is close to the piecewise linear curve in Fig.1. There is some ripple on the detected output as the RC filter does not provide perfect smoothing of the envelope.

Fig.11. Simulation result from the circuit in Fig.10.



Transconductance Amplifiers

Summing voltages directly is relatively difficult and the half-wave diode detector does not provide very high performance – real diodes may have too large a voltage drop to be used directly on low-level signals.

There are better approaches to addition and detection. Addition of signals is easily achieved using currents – simply connect all the current outputs together. This can be done using the version of the circuit in Fig.2 shown in Fig.9. The output of each amplifier in the cascade is fed to a transconductance amplifier (gain g_m). Transconductance amplifiers have an input of voltage and an output of current. The transconductance amplifier outputs are connected together to sum the currents. To achieve detection the transconductance amplifiers can have an absolute value characteristic (both positive and negative inputs give positive outputs), or a square-law characteristic (the square of both positive and negative values is positive). The current output can be converted to a voltage by passing it through a resistor and then a low-pass filter to provide a signal related to the amplitude envelope.

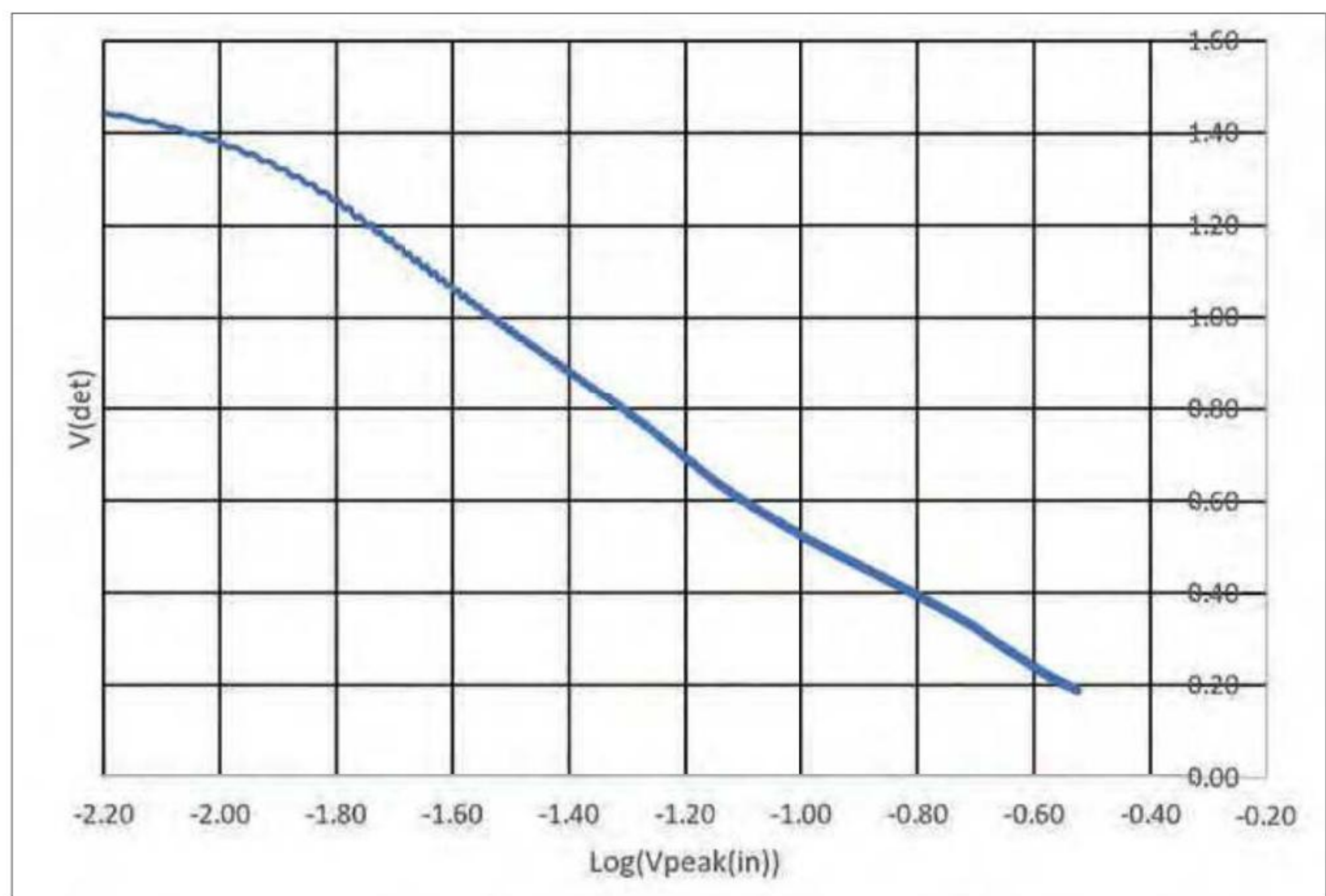


Fig.12. Plot of $V(\det)$ from Fig.11 vs the logarithm of the peak input voltage.



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The circuit in Fig.10 is a version of the circuit in Fig.9 in LTspice using behavioural current sources to implement transconductance amplifiers with an absolute function. Each current source has function $I=100e-6*abs(v(out3))$ – note the use of $abs()$. The gain is $g_m = 100\mu A/V$. The rest of this schematic is the same as Fig.4, but without the Bsum source as this function is replaced by the circuit in Fig.9. The current sources are paralleled to sum the currents and a constant current is added to provide positive offset when transconductance amplifier outputs are zero. The current is fed to an RC circuit to convert it to a voltage and provide low-pass filtering. The simulation result for the circuit in Fig.10 are shown in Fig.11 – this is just the $V(\det)$ signal, the $V(in)$ and $V(out1)$, $V(out2)$ and $V(out3)$ are the same as in Fig.5.

The negative slope of the $V(\det)$ response is like the response of the AD8318. To verify this is a log function, Fig.12 shows $V(\det)$ plotted against the log of the peak of $V(in)$. This was obtained by exporting the LTspice data to Excel. Fig.12 shows a more or less linear negative-slope relationship between the $V(\det)$ and the log of the peak input voltage, which corresponds with the AD8318 response (Fig.2 in the *RF Power Meter* article). As already noted, the LTspice circuit, although idealised, is a crude implementation as it only uses three stages rather than the nine in the AD8318. Various other details do not match exactly, but this example is sufficient to illustrate the basic principles of operation. Readers interested in knowing more of the specifics of how these devices operate should read the AD8318 datasheet and also the AD8307 datasheet, which is a logarithmic amplifier based on similar principles – the datasheet for AD8307 provides more details on the theory of operation.

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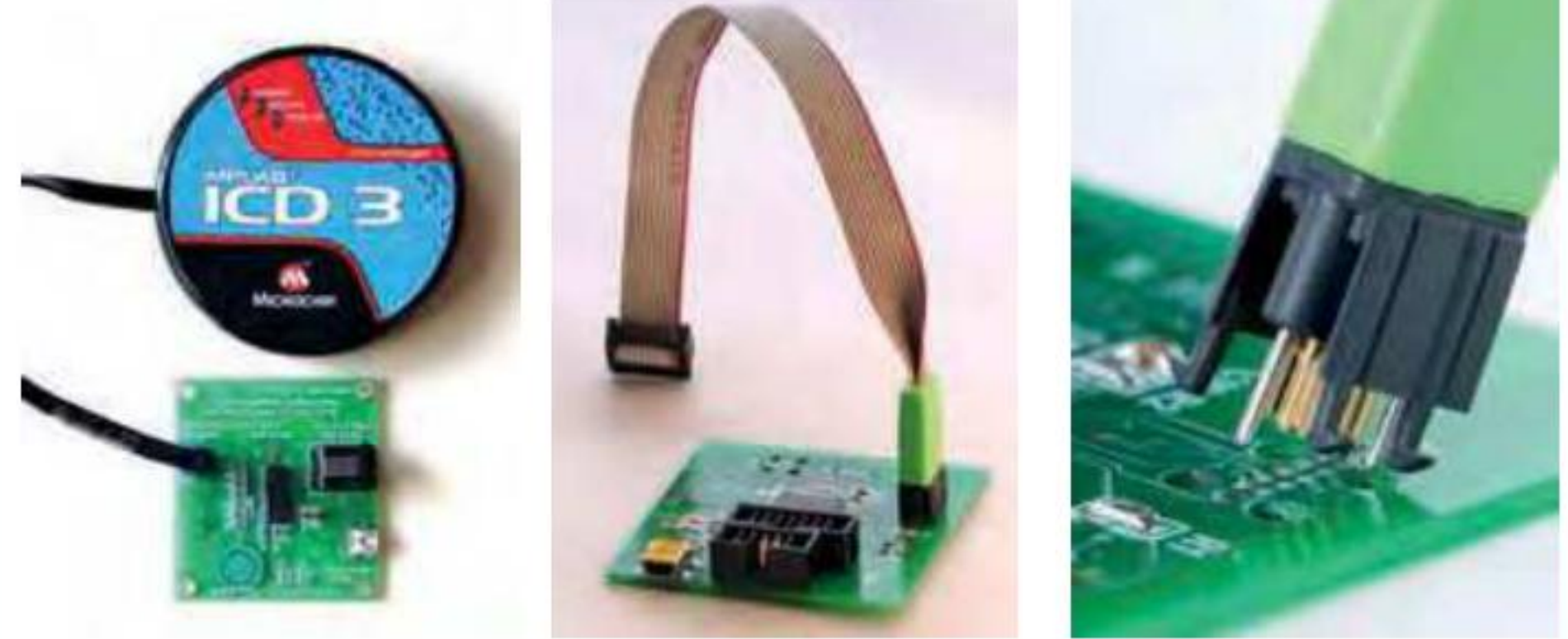
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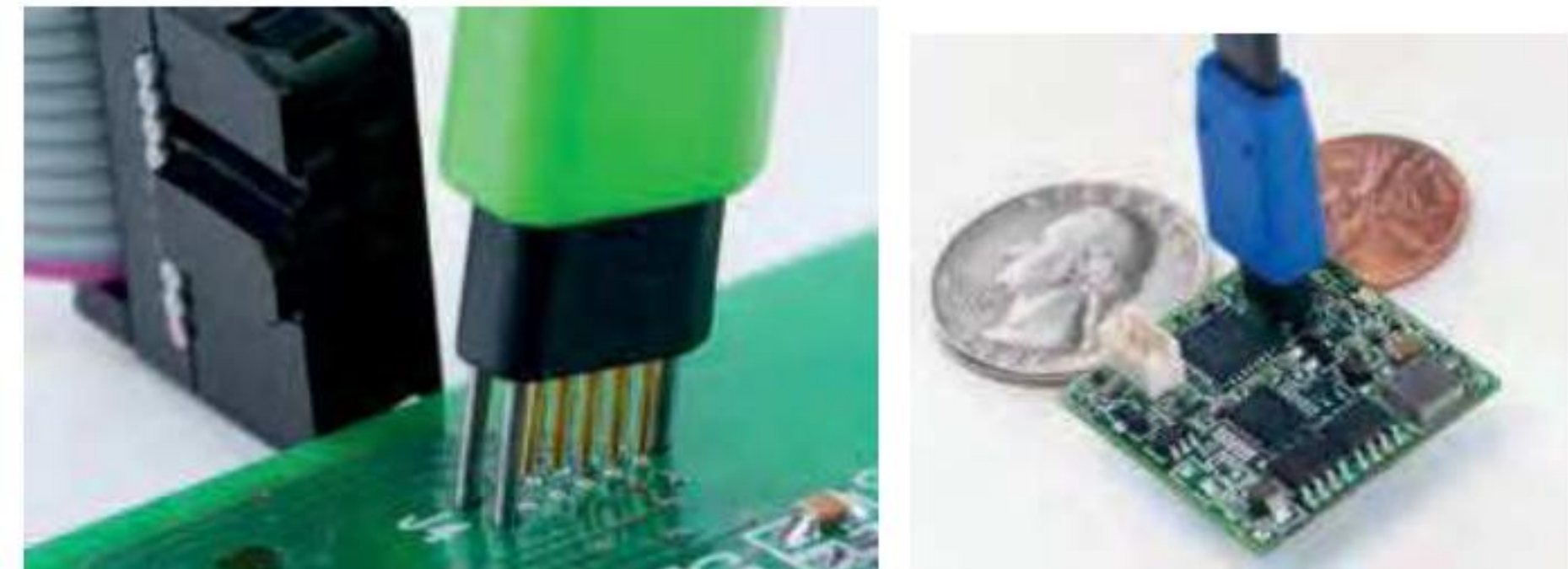
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In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

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PROJECT	CODE	PRICE
JULY 2018		
Touchscreen Appliance Energy Meter – Part 1	04116061	£17.75
Automotive Sensor Modifier	05111161	£12.88
JUNE 2018		
High Performance 10-Octave Stereo Graphic Equaliser...	01105171	£15.30
MAY 2018		
High Performance RF Prescaler.....	04112162	] £10.45 £8.45 £5.60
Micromite BackPack V2.....	07104171	
Microbridge.....	24104171	
APRIL 2018		
Spring Reverberation Unit.....	01104171	£13.95
DDS Sig Gen Lid.....	Black	£8.05
DDS Sig Gen Lid.....	Blue	£7.05
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MARCH 2018		
Stationmaster Main Board.....	09103171	£17.75
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SC200 Amplifier Module – Power Supply.....	01109111	£16.45



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Mike & Richard Tooley

The three sections of the *Teach-In 3* CD-ROM cover a huge range of subjects that will interest everyone involved in electronics – from newcomers to the hobby and students to experienced constructors and professionals.

The first section (80 pages) is dedicated to *Circuit Surgery*, *EPE/PE*'s regular clinic dealing with readers' queries on circuit design problems – from voltage regulation to using SPICE circuit simulation software.

The second section – *Practically Speaking* – covers hands-on aspects of electronics construction. Again, a whole range of subjects, from soldering to avoiding problems with static electricity and identifying components is covered. Finally, our collection of *Ingenuity Unlimited* circuits provides over 40 circuit designs submitted by readers.

The CD-ROM also contains the complete *Electronics Teach-In 1* book, which provides a broad-based introduction to electronics in PDF form, plus interactive quizzes to test your knowledge and TINA circuit simulation software (a limited version – plus a specially written TINA Tutorial).

The *Teach-In 1* series covers everything from electric current through to microprocessors and microcontrollers, and each part includes demonstration circuits to build on breadboards or to simulate on your PC.

ELECTRONICS TEACH-IN 4 – CD-ROM A BROAD-BASED INTRODUCTION TO ELECTRONICS

Mike & Richard Tooley

The *Teach-In 4* CD-ROM covers three of the most important electronics units that are currently studied in many schools and colleges. These include, Edexcel BTEC level 2 awards and the electronics units of the Diploma in Engineering, Level 2.

The CD-ROM also contains the full *Modern Electronics Manual*, worth £29.95. The Manual contains over 800 pages of electronics theory, projects, data, assembly instructions and web links.

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Mike & Richard Tooley

Teach-In 6 contains an exciting series of articles that provides a complete introduction to the Raspberry Pi, the low cost computer that has taken the education and computing world by storm.

This latest book in our *Teach-In* series will appeal to electronics enthusiasts and computer buffs who want to get to grips with the Raspberry Pi.

Teach-In 6 is for anyone searching for ideas to use their Pi, or who has an idea for a project but doesn't know how to turn it into reality. This book will prove invaluable for anyone fascinated by the revolutionary Pi. It covers:

- Pi programming
- Pi hardware
- Pi communications
- Pi Projects
- Pi Class
- Python Quickstart
- Pi World
- ...and much more!

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ELECTRONICS TEACH-IN 7 – CD-ROM DISCRETE LINEAR CIRCUIT DESIGN

Mike & Richard Tooley

Teach-In 7 is a complete introduction to the design of analogue electronic circuits. It is ideal for everyone interested in electronics as a hobby and for those studying technology at schools and colleges. The CD-ROM also contains all the circuit software for the course, plus demo CAD software for use with the *Teach-In* series.

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 - iii) Tone Control
 - iv) VU-meter
 - v) High Performance Audio Power Amp.

PLUS

Audio Out – an analogue expert's take on specialist circuits

Practically Speaking – the techniques of project building.



ELECTRONICS TEACH-IN 8 – CD-ROM INTRODUCING THE ARDUINO

Mike & Richard Tooley

Hardware: learn about components and circuits

Programming: powerful integrated development system

Microcontrollers: understand control operations

Communications: connect to PCs and other Arduinos.

Teach-In 8 is an exciting series designed for electronics enthusiasts who want to get to grips with the inexpensive, popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. It will provide a one-stop source of ideas and practical information.

The Arduino offers a truly effective platform for developing a huge variety of projects; from operating a set of Christmas tree lights to remotely controlling a robotic vehicle through wireless or the Internet.

Teach-In 8 is based around a series of practical projects with plenty of information for customisation.

This book also includes *PIC n' Mix*: 'PICs and the PICkit 3 – A Beginners guide' by Mike O'Keefe and *Circuit Surgery* by Ian Bell – 'State Machines part 1 and 2'.

The CD-ROM includes the files for:

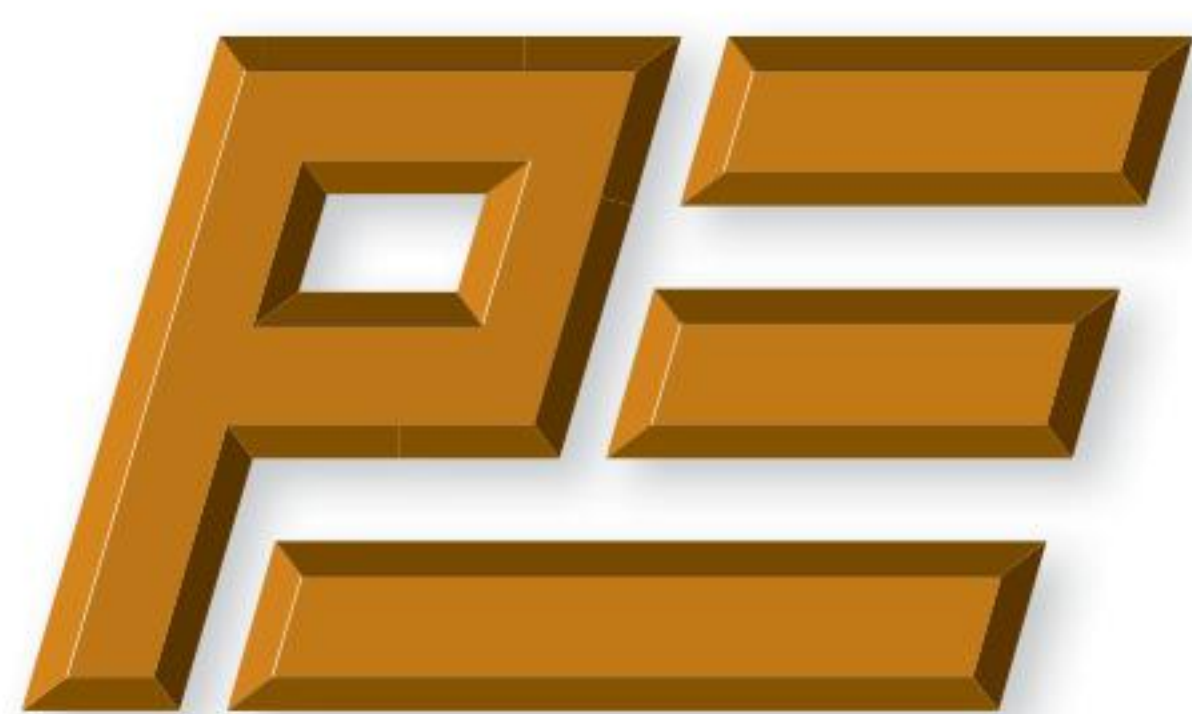
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Next Month – in the October issue

Mini Wi-Fi LCD BackPack

Besides a colour touchscreen, another very handy feature to have in a micro-controller module is wireless communications. WiFi is probably the most versatile method, as most homes and offices have WiFi networks. Once the micro has Internet access, the list of things you can do with it explodes! This low-cost project uses an ESP8266-based module which is both powerful and inexpensive.

High-power Ultrasonic Cleaner – Part 2

This large and powerful Ultrasonic Cleaner is ideal for bulky items such as mechanical parts and delicate fabrics. We've described its features and explained how it works. Next month, we'll move on to building it and getting it going!

USB SuperCodec – Part 2

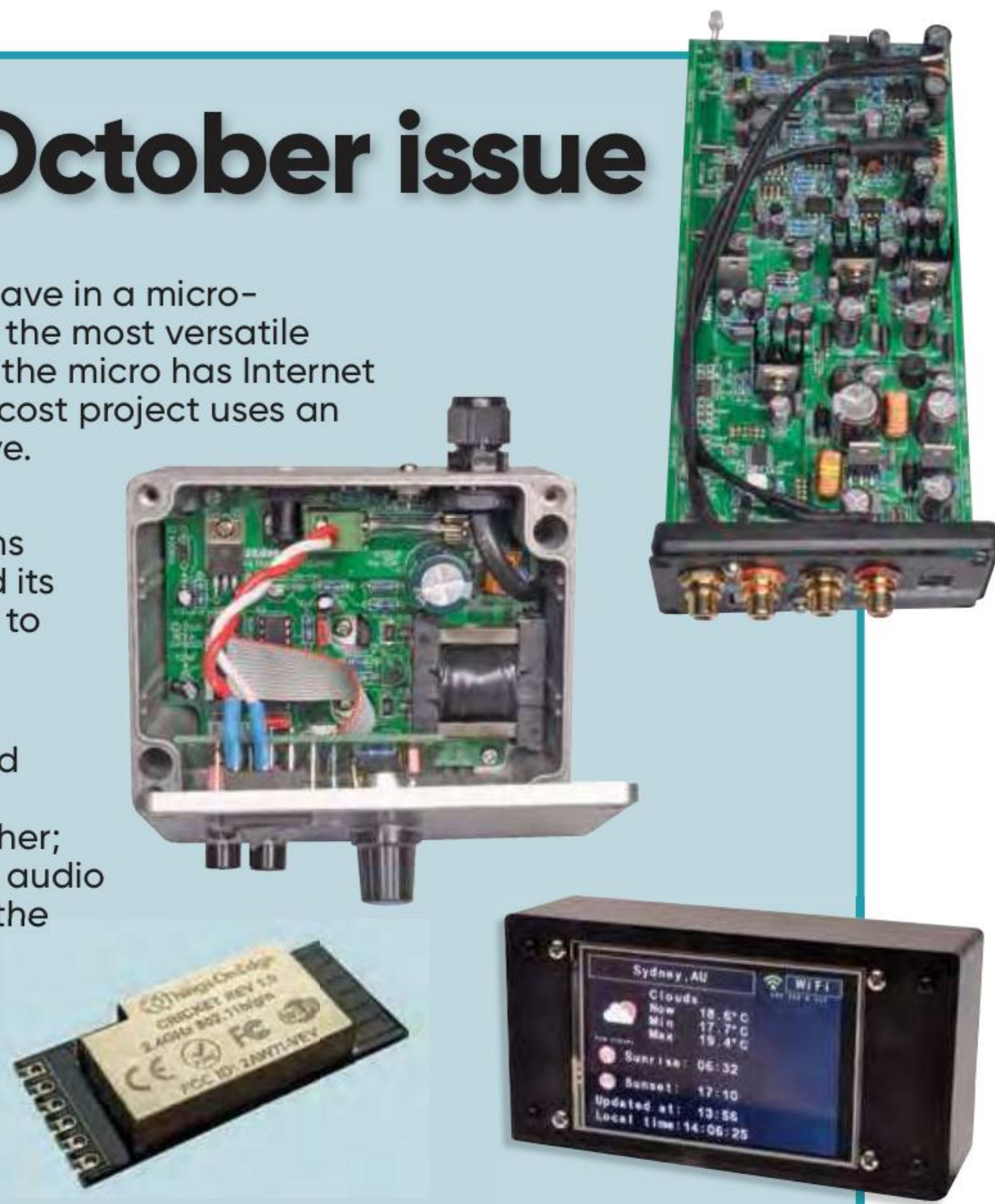
In the September issue we introduced our new USB Sound Card design which boasts unimpeachable recording and playback performance. It isn't only useful for recording and playback either; with some inexpensive software, it can make a very advanced audio signal analysis system. Now it's time to describe the details of the circuitry behind its phenomenal performance.

Cricket with Node-RED & Raspberry Pi

Back in the June issue we covered the remarkable Cricket IoT module. Next month, we look at using it with Raspberry Pi and Node-RED, an open-source graphical programming tool.

PLUS!

All your favourite regular columns from *Audio Out*, *Cool Beans* and *Circuit Surgery*, to *Make it with Micromite* and *Net Work*.



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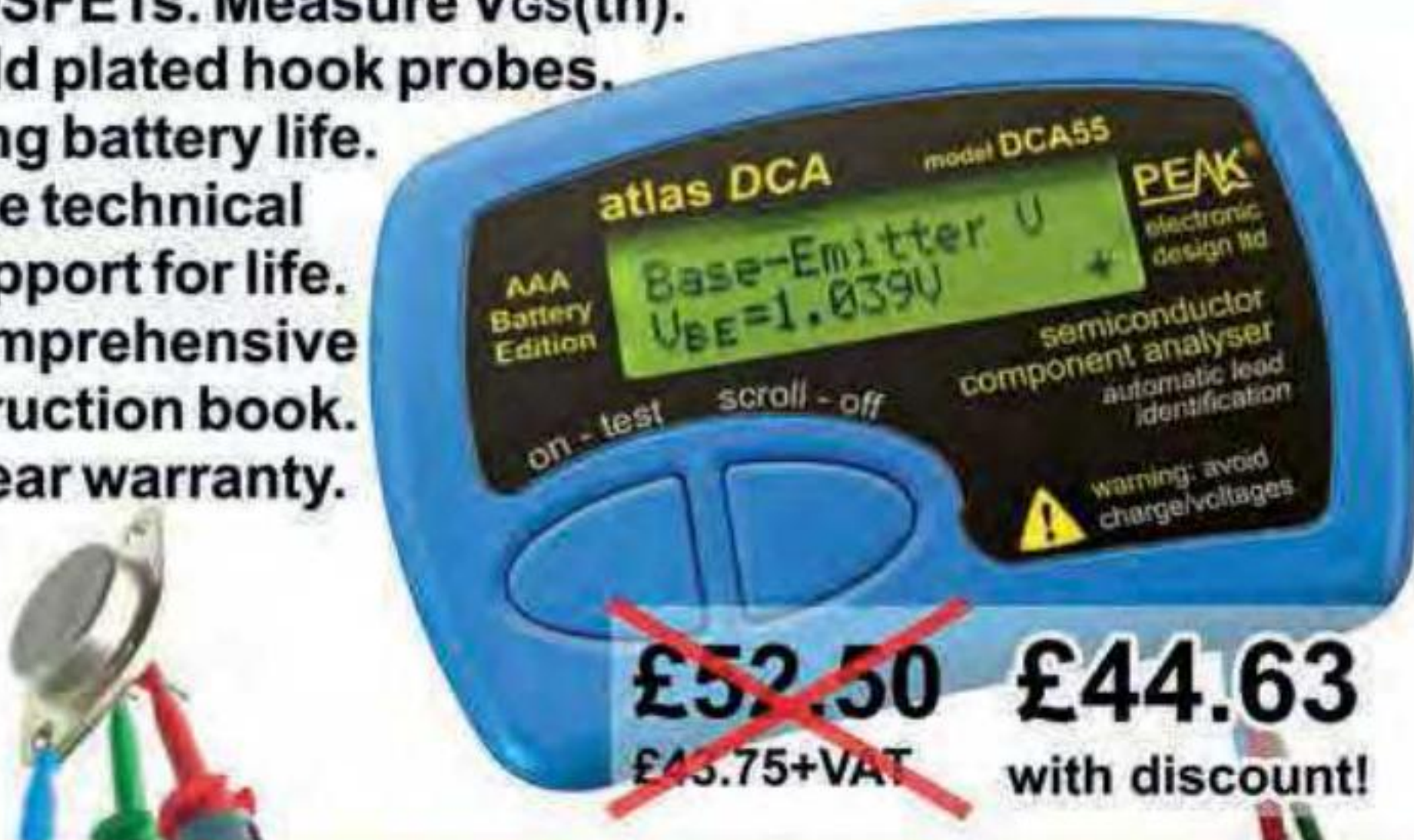
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